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IGNITION AND FLAME DEVELOPMENT IN THE CASE OF
DIESEL FUEL INJECTION

By Otto Holfelder

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IGNITION AND FLAME DEVELOPMENT IN THE CASE OF
DIESEL FUEL INJECTION*

By Otto Holfelder

SUMMARY

To investigate the process of ignition and combustion in the case of spray injection into heated air, a new form of apparatus is developed and the tests carried out with it described.

Photographs of the spray before and after ignition are obtained at frequencies of 500 pictures per second. Large windows in the bomb allow unobstructed observation. Pressures and temperatures are simultaneously recorded on oscillograms. Information on the initial conditions, ignition time lag, period of complete combustion, place where ignition starts, and general course of the combustion is obtained.

Different types of nozzles connected in various ways to the pump are investigated, and different fuels tested and compared under conditions of no turbulence. Tests on the effect of turbulence are being planned. Study of the combustion process is made using precombustion chambers.

The tests give first-hand insight into the phenomena occurring in diesel fuel injection, where actual engine conditions are simulated as far as possible. They enable the investigation of the ignition properties of various fuels to be made and the data thus obtained are probably directly applicable to the behavior of fuels in the diesel engine.

*"Zündung und Flammenbildung bei der Diesel-Brennstoff-Einspritzung." Forschungsheft 374, Beilage zu Forschung auf dem Gebiete des Ingenieurwesens, Band 6, September-October 1935, pp. 1-25.

I. INTRODUCTION

The rapidly increasing application of high-speed diesel engines has been accompanied by correspondingly increasing requirements in power output and running characteristics put upon this type of engine. It is only when it attains efficiencies and running characteristics comparable to those of the spark-ignition engine that the diesel engine will be able to compete successfully with the former and may then be expected to find application in the field of automobile and airplane engines.

The efficient use of the fuel through good intermixture with air is a primary condition for attaining high specific outputs and this is all the more important at the higher speeds, with the corresponding shorter combustion periods. The pressures in the cylinder during the process of ignition and combustion determine the running characteristics of the engine. Most of the investigation work on diesel engines that has been done in the last few years dealt with the problem of injection, ignition, and combustion and has greatly deepened our knowledge of this subject.

The various methods that have been used to obtain a good time and space distribution of the mixture have been comprehensively dealt with in numerous investigations. It has been shown that to obtain the optimum power output, a uniform atomization with high penetration of the fuel and uniform delivery of the fuel by the pump are of first importance. This holds true for the case where direct injection is used as well as for the case where a precombustion chamber, supercharger, or turbulence chamber is employed.

The variation of the pressure in the cylinder depends on the time of ignition and the manner in which combustion proceeds. Both of these processes cannot be regulated by varying the strength of the mixture alone; they are affected by the physical and chemical changes undergone by the fuel before combustion. The first investigations on the subject were therefore concerned with the determination of the curves of boiling and the points of ignition of the different fuels using special test apparatus. It soon appeared, however, that these investigations could not be used to form any definite conclusions as to the behavior of any two different fuels in the engine since the processes in the engine are subject to quite different conditions from those obtainable in the combustion apparatus.

The question whether the fuel, or at least the greater part of it, is vaporized or is gasified just before ignition, has always been a matter of dispute. The start of vaporization depends very much on the size of the drops as well as on the local temperature. Since all of these values are subject to large time variations and no method free from objections has been devised for determining the size of the drops, the computation of the amount of evaporation even when the greatest care is used can only be roughly determined. According to present-day views and the investigations of Boerlage and Broeze (reference 3), ignition occurs with the fuel in the vapor phase or some intermediate phase between the liquid and vapor. The entire fuel charge does not necessarily vaporize, but only a part of it. The view held formerly that the whole of the charge was gasified just before ignition was shown to be unacceptable. The gasifying of the fuel is equivalent to a cracking process. The oil gas arising from this process is less inflammable than the parent fuel and gasifying should therefore be avoided as much as possible.

In addition to partial vaporization, there apparently occurs a decomposition of the fuel through oxidation of the hydrocarbons, during which unstable peroxides are formed, the decomposition of which favors ignition. This theory of peroxide formation is not yet well developed. This much, however, appears to be certain, that although the peroxides themselves accelerate the ignition process, the addition of materials that have a tendency toward rapid peroxide formation does not aid the process. According to the results of I. D. van Dijck (reference 3), the tendency of the oil molecules to decompose at high temperatures is the most important indicator for the ignition efficiency of a fuel.

To compare the ignition properties of different fuels for the diesel engine the cetene number has been used; it gives a better value for the ignition lag than that obtained by the use of ignition-point apparatus. Unfortunately, cetene is too expensive for use in engine tests and other suitable materials of similar kind are not yet available.

The most accurate information on the fuel behavior in an engine and the efficiency of its atomization is obtained by the direct measurement of the ignition lag in the engine or in combustion bombs. Much useful information has been yielded by these methods in the last few years. Dif-

ferent ignition times and ignition lags have been obtained, depending on the method used for their measurement. However, all are agreed on the definition of ignition lag as the period extending from the beginning of injection to measurable ignition.

The sudden steep rise of the pressure on the pressure-time diagram, as given by an indicator having as little inertia as possible, has been used for the determination of the start of ignition and the measurement of the ignition lag. In other experiments ionization paths and the photocell have been applied to indicate the approach of the flame front at definite points in the combustion space and the ignition lag has thus been measured. Spectroscopic methods have also been used for the same purpose. Finally, sensitive thermocouples placed at various points in the engine have been used for the same purpose. Owing to the inertia of the apparatus used, all these methods are not free from objection. An accurate method for the determination of the ignition and combustion processes can only be obtained by directly photographing the flame.

The work under consideration was taken up in connection with the investigations which the author carried out on the forms of spray injected at high pressure. The purpose is to investigate not only spray forms during injection into a bomb containing hot compressed air, but also to observe the ignition and combustion through direct flame observation and simultaneous stroboscopic photography. Oscillograms of the temperatures and pressures in the bomb were obtained, using piezoelectric crystals as pressure indicators.

Since all other methods for the observation of the flame formation were indirect and not entirely reliable, it appeared to us that a large expenditure of time and preparation was justifiable. The planning and construction of the apparatus was begun in April 1932, but in view of the numerous difficulties met with, no reliable data could be obtained until the end of 1934. In the meantime there appeared the first reports on spark-flame photography obtained at the N.A.C.A. in the United States by A. M. Rothrock (references 22, 5), who employed a special test engine. Since his apparatus did not include a stroboscope, his photographs showed unclear light streaks whose borders indicated the flame path. Moreover, the disk-shaped combustion chamber of 22 mm (0.866 in.) width and 75 mm (2.95

in.) diameter was too small, so that the fuel drops were impacted on the windows even before ignition occurred and this rendered the spark photographs unclear and ill-defined.* Furthermore, an electric motor was used to drive the engine and it took some time for the combustion chamber to warm up. Self ignition was not much improved by warming the cylinder walls to 95° C. with preheated glycerin. The ignition lags up to values of 1 second measured by Rothrock indicate that his apparatus only imperfectly simulated the conditions in a diesel engine. The first flame pictures for the diesel engine were obtained by Mader (reference 15) in Germany as far back as 1926. Since, however, he had to work with exposure periods of about 1/3000 second, his pictures are also quite unclear.

Bird (reference 2) was the first one to photograph fuel sprays in combustion bombs.

II. APPARATUS AND PRELIMINARY EXPERIMENTS

After the experience gained from using injections into cold compressed air, it appeared to be desirable to use bombs with hot air and relatively large combustion space with large and broad windows so as to afford free and unhindered observation of the combustion process. The normal combustion chamber of the diesel engine itself could not be used for this purpose as the means of observation would have been very limited. In order to obtain clear and reliable data on the ignition and combustion process, the compressed air in the bomb has to be uniformly heated. The method of artificial outside heating of the bomb walls as used by Neumann (reference 19) and Hartner-Seberick in their experiments was not employed since the radiation from the walls of the bomb would lead to an uneven temperature distribution in spite of turbulence. Heating the air by

*In the N.A.C.A. publication referred to here (reference 23), the conclusion presented was that under the low temperature conditions existing in the N.A.C.A. combustion apparatus for this particular series of tests the injected fuel first vaporized and then if combustion did not take place, recondensed not on the glass walls of the combustion chamber but in the air in the chamber, so that the fuel was again in a liquid condition as extremely small drops. (N.A.C.A. Editor's note.)

means of precombustion of the mixture of methane, oxygen, and nitrogen, or hydrogen, oxygen and nitrogen, as proposed by Wentzel (reference 29) and von der Nahmer (reference 18), makes the arbitrary determination of the start of injection and the initial conditions in the bomb difficult. The incidental formation of the CO_2 and H_2O vapors and their effect on the combustion moreover has to be accounted for.

1. Diesel compressor.— A vertical single-cylinder MAN-diesel engine of 320 mm (12.6 in.) bore, 480 mm (18.9 in.) stroke (2,355 cu.in.), 220 r.p.m., and 50-horsepower output was used. The output was measured by a directly coupled d.c. dynamometer. The diesel engine could also be driven from the outside by an electric motor. The apparatus and connections were so arranged that the diesel engine could be used as a compressor working at reduced speed of about 100 r.p.m. This apparatus had already been briefly described in 1932. The ignition did not occur in the engine^{up} itself. Instead, the engine-combustion space was filled as far as possible by a plate placed upon the piston and a cylindrical combustion chamber was put in place of the air inlet valve.

Figures 1 to 4 show a sketch of the apparatus used and indicate the air circuit through the diesel compressor a, the bomb b, and receiver.

An air circuit was arranged so that as little heat as possible was lost in the passage of the air from the bomb to the cylinder except what was lost through conduction at the walls. In addition, the air in the receiver was electrically preheated so that steady conditions were attained in a short time.

Several compression strokes were required to obtain any desirable pressure in the combustion bomb because of the large volume of the combustion space compared with the displacement volume of the engine. An auxiliary valve g, compensated the compressor for any air that may have been lost during the pumping strokes and exhaust. As soon as the correct pressure has been reached in the bomb, an electromagnet releases this valve and by holding it open, allows the compressor volume to communicate with the outside air. The compressor was then running light and the bomb was disconnected from the compressor by pressure valve c, and was ready for the injection.

The final temperature in the bomb may be controlled by regulating the flow of the air and the amount of the preheating. Special emphasis was laid on the regulation of the temperature in the bomb in spite of the difficulties that were met with, since temperature exercises a more important influence on the combustion than the air density.

In spite of the water cooling, strong heating of the cylinder could not be avoided so that partial evaporation of the lubrication oil and the danger of oil explosions might have been expected in addition to the danger arising from the highly compressed air mixed with oil vapors in the bomb. To avoid the contamination of the air in the bomb with the evaporated lubrication oil, the latter was replaced by colloidal graphite. No trouble from this source was found when graphite lubrication was used. A safety valve set for 60 atmospheres afforded further protection against sudden rises in pressure.

2. The combustion bomb.— In designing the bomb, a primary consideration was that the spray coming from the nozzle should as far as possible avoid contact with any walls. From previously obtained results on spray speeds, penetration, and combustion periods, it was decided that a combustion space of cylindrical shape, about 400 mm (15.75 in.) long and 100 mm (3.94 in.) in diameter (191.6 cu.in.), would fulfill the necessary conditions. Due to this relatively large combustion space, the pressure was required to be built up in several stages.

The weakening of the cylinder wall along its length resulting from the inset of the 300 mm (11.81 in.) long and 40 mm (1.57 in.) wide observation window *k*, was compensated as far as possible by reinforcement around the rims. (See fig. 1.) The entire bomb was made of one piece of steel, 45 kg/mm² (64,000 lb./sq.in.) strength. Great difficulties were met in the choice of suitable glass for the windows. Preszhart-glas of 35 mm (1.38 in.) thickness was found to be unsuitable on account of its inner expansion and Sekurit-glas of 12 mm (0.47 in.) thickness was finally chosen. This glass proved to be an excellent choice, being able to withstand continuously the pressure of 60 atmospheres at a temperature of 450° C. Once the glass did break with explosive force; it smashed into blunt pieces so that the danger for the bystanders was less than would have been the case had Preszhart-glas been used. After the first explosion the entire bomb was surrounded with a sheet metal screen as a further protection. No window cleaners were

required on the inner sides of the windows since the fuel spray did not come in contact with them and thus did not obstruct the clear view.

The nozzle holder with replaceable nozzles was fixed in a water-cooled jacket along the axis of the cylindrical combustion space. The entire bomb was firmly pressed on the cylinder cover and held by tension rods.

The by-pass valve d, was placed in the upper end of the bomb. As this valve was constantly exposed to the hot air stream, it had to be made up of special heat-resisting material. The opening of the valve and hence the size of the cross-sectional opening of the throttle could be adjusted by hand by means of a fine screw. In this way the compression pressure and the temperature could be controlled. By means of a lever arrangement, this valve could instantly be closed electromagnetically when the desired charge in the bomb was obtained.

A safety valve n, which could be brought into action as soon as a pressure of 70 atmospheres was exceeded, was likewise connected to the bomb. In a hydraulic pressure test made at 80 atmospheres, only slight elastic deformations could be observed, but no permanent change in form was found. Connection to a usual spring manometer allowed continuous observation of the pressure in the bomb. Several short tubes along the bomb axis were provided for the insertion of the thermocouples.

Accurate pressure measurements were obtained with a quartz indicator (fig. 5) and registered on an oscillograph. Various forms of indicator were experimented with, during which it was found that changes in the zero position and sensitivity were brought about by expansion of the housing as well as by variations in the form and elasticity of the pressure membrane at high temperatures. Following the suggestion of S. Meurer, the form of indicator shown in figure 5 was finally chosen. This indicator does not allow the zero point to be shifted with expansion of the housing. The entire pressure was taken up by a thin copper membrane b. This indicator was also found suitable at the high temperatures.

The entire bomb was not heat insulated on the outside, but only the connecting pipes. Since the bomb was not insulated, it took about 80 minutes for the compressed air to reach the ignition point. Several methods were tried in

order to reduce the time. The bomb was at first fitted on the inside with asbestos-like plates of "Europil" with Neusilber coating and the time for heating up was thus reduced to about 50 minutes. It was not found feasible to provide electric heating between the mica and Europil plates. The best insulated material was found to be a cylinder of sheet metal enameled on both sides, placed in the bomb cylinder at 3 mm (0.118 in.) separation.

3. Fuel injection.— The experiments were designed to simulate present-day vehicle engines as far as possible. To have made too many changes in the apparatus for the purpose of obtaining better observation, would have falsified the whole picture of the combustion process as it actually occurs in an engine. For these experiments a Bosch pump, type PE 1B 100/100, was chosen as this is the pump used for most vehicle engines.

It was now necessary to redesign the pump so as to deliver a single injection of any desired quantity and at any desired speed into the bomb chamber.

The fuel pump was directly coupled to a d.c. motor whose speed could be varied between 250 and 1,500 r.p.m. A control rod actuated by an electromagnet regulated the amount of injection for any speed of the pump. An additional magnet brought the regulating rod back to its original position as soon as the requisite fuel quantity was delivered. It was not found advisable to replace the second magnet by a spring since this would have put too great a load on the first magnet.

Figure 6 shows the arrangement of the fuel pump and drive with control magnets. The current for both magnets was taken off sliding contacts on rings around the pump. By means of an interrupter arrangement current was supplied to the magnets during a single rotation only. Figure 7 is the diagram of connections and will be further discussed later on.

A heavy flywheel was fixed to the pump shaft to give a more uniform charge delivery. This arrangement worked satisfactorily at all speeds and cut-offs as long as care was taken to see that the pipe between the pump and fuel valve was always filled and was under the closing pressure of the needle valve.

4. Preliminary experiments.— After experimenting for

some time and making some minor changes in the apparatus, uniform ignition was obtained in the bomb. The work of constructing the photographic apparatus was then begun, taking into consideration the intensity of the light of the flame. Little would be gained by naked-eye observation on account of the very short times involved.

Pictures were first taken with ordinary photographic apparatus. All sunlight was cut off from the bomb, a 4.5 aperture diaphragm being held open in front of the objective. A single picture was taken of the ignition and combustion process using the light of the burning flame itself. Figures 12 to 15 show photographs of two magnifications thus obtained. The shape of the burning spray can be easily recognized, though it can give no information on the place of ignition, time of combustion, and path of the flame. In fact, any attempt to interpret these pictures in greater detail would lead to error.

Some interesting facts may nevertheless be observed from figures 12, 13, and 14. These pictures were obtained at temperatures near the ignition limit. Within this region of temperature a mass of burning fuel droplets could be observed by eye. On these photographs the paths of these drops appeared as lines somewhat resembling a comet's tail. The light intensity of the drops was so feeble, however, that they could not register on the stroboscopic photographs that were taken later on, although they could be observed by the naked eye.

To obtain a large number of photographs, the apparatus shown in figures 8 and 9 was used after other forms of apparatus such as the Lindner-Schlieren were considered. The Lindner-Schlieren method, using spark photography, (reference 12), was not employed because only seven pictures could be taken for each injection and, besides, other difficulties in the way of uniform illumination were met with.

5. Photographic apparatus.— At this point it was debated whether or not it was advisable to buy one of the forms of apparatus put out on the market and thus be spared the trouble of developing new apparatus. Several important objections were found, however. For a picture frequency of 500 pictures per second and the combustion period estimated as 0.08 second, about 80 cm (31.5 in.) of film would be required for each process (reference 6). This small useful film length required a roll of film of about 40 m (131.20

ft.) length in order to take account of the starting and stopping of the film. Besides, at the above-mentioned frequency, the pictures obtained would be very much diminished in size and would not allow of clear magnification. For these reasons an endless film band on a rotating drum (reference 14) and not the usual type of film roll was used.

As no suitable apparatus of this type to meet all of our requirements was on the market, it had to be newly designed and built in the Dresden Machine Laboratory. The main specifications were these:

1. Picture frequency, about 500 per second.
2. Number of pictures for each injection, about 25 to 30.
3. Pictures to be reduced no more than $1/4$ the natural size.
4. Greatest possible definition up to speeds of 10 m (32.81 ft.) per second; illuminated point exposure about 1×10^{-5} seconds.
5. Illumination to be restricted to the film drum.
6. Cut-off of illumination to be possible at any point on the drum circumference.

Figures 8 and 9 show the apparatus. It consists essentially of a slotted disk a, rotating up to 4,500 r.p.m.; film drum o; light cut-off h; rotating diaphragm g; and the optical system. All parts are firmly fixed to two channel beams and held in the optical axis of the bomb window.

At first it was planned to have the disk a, made of duralumin, but this was found to be unsuitable on account of slight distortions and expansions. Thin-sheet metal of uniform strength, as well as pasteboard, was also tried but both were similarly found unsuitable. It was finally decided to have the disk made of 0.8 mm (0.0315 in.) thick Novotex pressed in between two plates. Eight slits 1 mm (0.0394 in.) wide and 100 mm (3.937 in.) long were cut around the circumference and determined the picture frequency and light-exposure time. The disk required a $1\frac{1}{2}$ -horsepower driving motor.

At the housing of the disk is the round axle box n, joined to the film drum o, by a bayonet catch. The film drum is driven by a special motor q, at speeds up to 1,150 r.p.m. The drum speed must be accurately adjusted to the disk speed to avoid any overlapping or too much separation of the pictures. Special highly sensitized double-coated super-agfa-Röntgenfilm was used.

On the side of the disk facing the bomb is the diaphragm g, actuated by an electromagnetic release mechanism so as to admit light during one rotation of the drum only. The photographic apparatus was synchronized with the injection apparatus by means of a third controller drum on the pump shaft.

In order to obtain complete information on the whole combustion process, pictures of the spray before as well as after ignition were desirable. These were obtained by means of silhouette photographs similar to those used in spark photography (reference 8). As great difficulties were found in synchronizing the spark illumination, an arc light taking 20 amperes at 40 volts was employed. Extended photometric experiments, which were conducted with the friendly aid of A. Weise, showed that a light intensity of as much as 150,000 lux could be obtained by concentrating the light rays from the arc through two condensing lenses of 150 mm (5.91 in.) and 300 mm (11.81 in.) diameter, even after account had been taken of all the light losses. To obtain a good silhouette on the film, an exposure time of 0.000002 second would have been sufficient, whereas in practice a period of double this time was provided for.

It was necessary to reduce the light intensity of the arc so as not to block out the light of the burning spray itself and thus spoil the photograph. This was done by placing a strong green filter between the arc and the bomb. Figure 16 shows a photograph of the apparatus. In the foreground may be seen the large condenser, next the bomb, and the housing for the disk. Figure 10 shows the set-up of the entire apparatus.

III. MEASUREMENTS AND CALIBRATIONS

1. Combustion bomb.— The combustion bomb is set in place of the inlet valve on the diesel engine, which is used as a compressor of 38.6 liters (2,355.5 cu.in.) dis-

placement volume. The remaining nonuseful volume in the diesel cylinder above the piston and in the valves amounting to 0.91 liter (55.5 cu.in.). The total volume of the bomb amounted to 5.512 liters (336.4 cu.in.). The compression ratio was therefore about 1/7. After three strokes of the piston a pressure of 54 atmospheres was reached in the bomb. Temperatures of 400° to 450° were reached at 1-atmosphere pressure after rather long preheating of the bomb with the relief valve kept somewhat open. After five or six compression strokes the temperatures of about 450° to 570° at 20 to 40 atmospheres gage pressure were reached, depending on the amount of preheating of the bomb. The injections and combustion occurred at these initial conditions.

For reasons of safety the combustion pressures in the bomb should not exceed 60 atmospheres. This condition determined the maximum amount of fuel spray that could be used without giving rise to excessive pressures. For a pressure of 20 atmospheres, the quantity would be about 750 mg, an amount that could not be delivered by the pump used at the time. Combustion with large excess air therefore took place in the bomb. Since, however, the air turbulence was slight and the spray cone occupied only a small portion of the air space in the bomb, the excess air in the spray was actually less. The volume of air required for combustion depends on the pressure and temperature according to formula

$$V_0 = V \frac{T_0 P}{P_0 T}$$

$$P_0 = 10,000 \text{ kg/m}^2 \text{ (2,048.2 lb./sq.ft.)}$$

$$T_0 = 283^\circ \text{ K}$$

For complete combustion an amount of fuel B, could be injected into the bomb, where

$$B = V_0 \frac{1}{L_{\min}} = f(P, T)$$

Whereas the total volume of the bomb space is 5.5 liters (335.6 cu.in.), the spray itself occupies a much smaller volume. From experiment, it was found that the cone angle of the spray had an average value of 20° and a penetration of about 40 cm (1.57 in.). With these values the volume of the spray was computed to be about 1.6 liters (97.34 cu.in.).

Figure 11 shows the amount of fuel spray into the bomb as a function of the pressure and temperature for excess air coefficient $\lambda = 1$. The region to the right of the temperature lines represents the region of excess air $\lambda > 1$, and that to the left of the lines is the region of efficiency of air $\lambda < 1$. One set of curves refers to the bomb volume, the other to the spray volume. The pressure increment

$$\Delta p = p_2 - p_1 \text{ (kg/cm}^2\text{)}$$

is computed from the amount of fuel injection $Q_B = B H_u$ (k cal) with the aid of the equation

$$Q_B = \frac{A}{\kappa - 1} V (p_2 - p_1) 10^4$$

Assuming the value of 1.35 for κ and substituting the volume of the bomb in the equation, Δp comes out equal to 27.0 B.

Figure 36 shows the variation of the pressure increase Δp with fuel charge B . On the same diagram is also shown the decrease of the excess air coefficient with increasing charge λ , and λ_2 referring to the total bomb volume and spray-cone volume, respectively. The rise in temperature in the bomb after ignition is measured by considering the amount of air and fuel in the bomb. The heat of the air in the bomb of volume 5.51 liters (335.63 cu.in.) is

$$Q_L = 0.065 p_1/T_1 [C_v]_0^{t_1} t_1 \text{ [k cal]}$$

According to Rosin, for each kilogram of fuel with excess air

$$\begin{aligned} V_{\min} - L_{\min} &= 0.268 \times 10^{-4} \text{ [mol/g]} = 11.1 - 10.5 \\ &= 0.6 \text{ mm}^3/\text{kg} \text{ (46.71 cu.in./lb.)} \end{aligned}$$

The amount of heat after combustion is therefore

$$Q_v = (0.065 p_1/T_1 + 0.268 \times 10^{-4} B) [C_v]_0^{t_2} t_2$$

and therefore

$$t_2 = \frac{0.065 \frac{p_1}{T_1} [C_v]_0^{t_1} t_1 + 10 B}{0.065 \frac{p_1}{T_1} + 0.268 \times 10^{-4} B [C_v]_0^{t_2}} [C^\circ]$$

Had the excess air been neglected, this equation would not be sufficiently accurate for low fuel charges. The computed values of t_2 are given in figure 36 as a function of the fuel charge B . If the bomb volume be considered as the combustion space of a diesel engine cylinder, the latter would have a displacement of about 75 liters (4,576.7 cu.in.) at a compression ratio of 16. For $\lambda = 1.6$, 3.45 g (0.008 lb.) of fuel could be burned for each working stroke. The bomb would then correspond to an equivalent 2-stroke-cycle diesel engine of 350 r.p.m. and 400 horsepower per cylinder. The actual injected fuel quantities, amounting at most to 270 mg, correspond to a cylinder output of about 31 horsepower.

2. Fuel injection.— The performance of the Bosch fuel pump was first investigated (figs. 37 to 39). Figure 37 gives the lift curve of the pump as a function of the camshaft angle α , with different cut-offs. Figure 38 shows the discharge volumes at different cut-offs at 300 atmospheres injection pressure and speeds of 300 to 800 r.p.m., where V_r is the computed value, V_{pr} the measured value. On account of the length of the delivery tube of 2 m (6.56 ft.), irregularity of the discharge caused by oscillations in the tube was sometimes observed and could not entirely be avoided. The computed angles and times for the pump discharge at the different settings are given in figure 39. They agree fairly well with those obtained from the photographs. Bosch valves giving spray angles of 4° to 8° were used.

3. Photographic apparatus.— The five essential requirements for this apparatus have already been mentioned. Figure 40 shows the exposure times for different stroboscopic disk speeds. Three different times are distinguished (fig. 40): $t_1 = \frac{AB}{v_s}$ determining amount of film blackening, $t_2 = \frac{AB + CD}{v_s}$ determining the degree of definition, $t_3 = \frac{EG + GH + HE}{v_s}$ total exposure time determining picture distortion, where v_s is the disk speed, v_f is the film drum speed in meters per second, and AB is the slit width. A speed of 3,250 r.p.m. for the disk is required to give an exposure time of 1×10^{-5} seconds. A definite speed of the film drum must correspond to any speed of the disk in order to have an even picture distribution on the film.

The relation is

$$n_s = \frac{r_f}{br_{sm}} n_f = K_{n_f} = 3.56 n_f \text{ (r.p.m.)}$$

where $b = 1.5$ cm (0.45 in.) is the distance apart of the photographs on the film, r_f and r_{sm} the average radii of the drum and slits. The relation is graphically shown in figure 40. There were eight slits in the disk at an average separation of 23.9 cm (9.41 in.). The time t_w , required for the light to pass from a given point on one picture to the corresponding point on the next picture, and the picture frequency ν , are given in figure 41 as functions of film drum speed n_f . The degree of definition and amount of distortion in millimeters are also shown on the same figure. At the usual speed of 900 r.p.m., the photographs obtained were sufficiently sharp, the deviation from a sharp image not exceeding 0.15 mm (0.006 in.). The distortion of about 0.6 mm (0.0236 in.) was within tolerable limits. The computations were carried out with reference to the times t_1 , t_2 , and t_3 . The degree of definition u , and amount of distortion z , brought about by the motion of both object lens and film drum were computed. Assuming an average value for the spray velocity and a combustion speed of 13.5 m/s (44.3 ft./sec.), and a size diminution of photograph of 0.22, $u_o = v_o t_2$ (mm) where v_o , the spray velocity, is 3,000 mm/s (9.8 ft./sec.). The corresponding value for u_f is $u_f = v_f t_2$ (mm). The distortion z_o , due to motion of the object lens is $z_o = v_o t_3$, and the distortion z_f , due to film motion, is $z_f = v_f t_3$ (mm).

The size of film drum and optical arrangement allowed 28 pictures to be obtained on the drum circumference. To avoid double exposure and allow for the proper action of the light shutter and the instantaneous light cut-off, only 26 pictures were taken, of which 14 to 16 were sufficient for interpretation.

IV. PROCESS OF IGNITION AND COMBUSTION AND INTERPRETATION OF PHOTOGRAPHS

The test was conducted in the following manner: The

engine used as compressor was preheated an hour or so until a temperature of 400° to 450° was reached, and the charging process then begun after closing the by-pass valve. After two to three compression strokes there was a further rise in temperature to about 550° with gage pressure of 25 to 30 atmospheres. Further increase in bomb pressure did not appreciably raise the temperature. There was observed, on the contrary, an appreciable drop in temperature, explained by the fact that after two or three suction strokes, fresh unpreheated air was drawn into the compressor. Moreover, the heat conduction and radiation increased at the larger densities so that the additional heat of compression was not sufficient to cover the increased heat loss. It was not considered advisable to improve the heat insulation of the bomb because of possible injury to the glass. When the temperature had reached the desired value, the injection and photographic apparatus was brought into action. The pressures and temperatures in the bomb were read simultaneously and in several cases also recorded on the oscillograph. The flame was likewise observed visually. The energy set free in the confined space in the bomb is converted into a sudden pressure and temperature rise which soon dies down after the heat exchange has been effected. After combustion the exhaust gas is allowed to escape by opening the by-pass valve in the bomb, closing the air valve in the compressor, and opening a fresh-air valve of large cross-sectional area in the manifold. After the bomb has been scavenged and the bomb has reached the proper temperature, it is freshly charged with air for the next trial.

Figures 17 to 19 show photographs obtained with gas-oil injection. The picture frequencies ranged from 300 to 500 per second according to the speed of the film drum. They were obtained as negatives and then copied. Originally obtained at a reduction in size of 22 percent, they are here given reduced to 15 percent of natural size. Figure 66 shows a case of good combustion with average ignition time lag. The start of combustion appears to be at the edge of the spray at its upper third portion. A green filter had been used to obtain a clearer picture of the spray by its own light. The first three pictures are silhouettes. The intensity of the darkening is an indication of the spray density and degree of atomization at different points. The use of a definite picture frequency makes it possible to determine the flame speed, ignition lag, and period of combustion. There is another very important characteristic to be observed in the photographs and that is the schlieren formation due to differences in density of the combustion prod-

ucts. Using approximately parallel light rays, these various densities appear as dark lines. Beginning with the fifth picture of figure 17, the outlines of the spray show marked schlieren formation. The succeeding pictures of the same figure at their upper portions show up particularly well the difference in the effect of the light on pure air and exhaust gas. Since the air in the bomb before ignition has no appreciable motion of its own, the lines appear only on the spray itself. The appearance of schlieren formation is of particular importance when the light of the flame is weak and not sufficiently effective on the film. In this case, however, the ignition lag may still be determined by the appearance of schlieren formation on the photograph (fig. 21). By using a spectroscope in connection with flame photography, still more far-reaching conclusions may be drawn, particularly with respect to O_2 , CH, and OH radicals.

The choice of color and thickness of filter was a matter of considerable importance in this connection. Figure 18 shows, for example, a photograph obtained with a blue filter. In this case the flame pictures appear as silhouettes, showing the light from the flame was less effective than that which filtered through from the arc. Such pictures are quite unsuitable for distinguishing the nonburning from the burning spray. (See also fig. 33.) For this reason, a blue filter was not generally used.

Figure 19 shows that schlieren do not appear at a misfiring, only a silhouette being observable. At the end of injection the bomb space again becomes perfectly transparent. The view remains clear up to the last picture, although a considerable part of the injected fuel has meanwhile evaporated. This shows that the streak formation does not originate from the evaporation of the fuel. Nor are the streaks affected by the color of the filter.

V. INJECTION OF GAS OIL

The apparatus could be used to test the suitability of different diesel fuels by a reliable objective method. The American fuel oil tested had a lower heat value of 10,014 k cal/kg (18,025 B.t.u./lb.) and specific weight of 887 kg/m³ (55.37 lb./cu.ft.) at 20°.

1. Ignition lag and combustion using a Bosch needle valve (Zapfendüse).— Figures 20 to 25 show photographs ob-

tained using a Bosch valve type DN4S1 with 4° spray angle. Figures 20 and 21 were obtained at the lower limit of kindling temperature. Whereas figure 20 still shows a bright flame, figure 21 shows that the flame was too weak to affect the film, though still observable by naked eye. In this case the ignition time lag was obtained from the schlieren formation. Figure 20 shows quite a long ignition lag after which the flame spreads more and more downward. The flame shows a rather distinct outline which indicates that the spray had not yet reached air that was hot enough for the transition to the state of combustion to be very noticeable.

Figures 20 and 21 likewise show up the effects of large differences in the amount of fuel injected. During all these tests the fuel cut-off at the pump was varied so as to obtain a relation for the effect of amount of fuel charge on ignition lag and flame formation. From all the tests it was found that by cutting down the fuel quantity to approximately one-half, that is, from 270 mm³ (0.0165 cu.in.) to 140 mm³ (0.0085 cu.in.), the ignition lag was reduced about 10 to 15 percent. These values, lying within the limits of experimental error, did not make it possible to obtain the desired relation. The probably increased ignition lag with quantity of fuel charge may possibly be explained by the fact that the degree of atomization and distribution of the fuel became worse with increased fuel charge, and the larger fuel quantity requires more heat energy from the air for ignition. The brightness of the flame is, however, considerably greater for the larger fuel charges as comparison of figures 20 and 21 shows. No appreciable effect of increased injection pressure above 300 atmospheres on the ignition lag could be observed.

Figures 22 and 23 were obtained at higher bomb temperatures and show smaller ignition lags. For figure 22 a pintle valve type DN 12 SD 12 was used, allowing a particularly uniform atomization of the fuel. The spray form is therefore somewhat different from those shown in the other photographs. It is a fact worth noting that the flame spreads very quickly from the outer edge of the spray to the core, bursting the core to a certain extent. From this it may be concluded that the atomization was very fine and uniform at the inner part of the spray cone. At the tip of the spray, on the other hand, the atomization appears to have been coarser since it took longer for the flame to arrive at the tip. Compare with figures 17 and 23. The same phenomenon was observed also in other tests where,

on account of the oscillations in the tube, the nozzle pin-tle was almost closed for a short time so that the spray was thinner and the inner portion of the spray soon reached the conditions for ignition. In no case, however, was the flame found to start from the core. L. Breves (reference 4), on the basis of his ionization tests on a Krupp-Moodag two-stroke diesel engine, assumes the possibility of ignition at the spray core. He employed nozzles of 0.3 mm (0.0118 in.) bore. The theory of L. Breves, that the rapid heating at the flame edge leads to decomposition products which first ignite at higher temperatures, could not be tested since it was not possible to measure the very small ignition lags (0.00087 to 0.00150 second) measured by his ionization method. The reliability of this method is, however, questionable since not only the occurrence of ignition but also any strong temperature and pressure change may be indicated by the ionization. Figure 23 shows the flame starting at the outer edge of the spray 3 cm (1.18 in.) beneath the nozzle opening. Only 21 cm (8.27 in.) of the 30 cm (11.81 in.) long observation windows were illuminated by the arc lamp. Only when the flame had penetrated a distance more than 23 cm (9.06 in.) from the nozzle opening, which occurred for large injected fuel quantities, was the rest of the window illuminated and the entire width of film utilized.

When the bomb temperature is increased by compression to about 550° C., ignition lag values of about 0.0025 second are obtained, of the same order of magnitude as those obtained for the running engine by other means. Here, too, it is clearly seen how the ignition starts at the edge of the spray. Apparently those parts of the spray which are most finely atomized and lose their energy of motion soonest, rapidly taking up heat from the air, ignite first.

From these and the remaining photographs, it may be concluded that combustion of the fuel sets in at some intermediate condition between liquid phase and gas phase, starting mostly at the spray edge, but also, under conditions of unusually fine atomization, at the inner core. No doubt partial evaporation as well as formation of gas occurs in addition to chemical reaction with the oxygen in the air. This conclusion may be drawn from the fact that the spray at its outer edge becomes transparent before ignition, as shown on many photographs with both large and small ignition lags. The transparency may be caused by the evaporation as well as by increased atomization and dispersion. The assumption that complete or extensive evapora-

tion takes place before ignition can hardly be accepted, since as Tausz and Schulte (reference 27) have shown ignition may occur with the fuel drop at 200°, whereas the drop completely evaporates at a temperature of about 400°.*

Figures 24 and 25 show clearly how the process of combustion, for short ignition lags, is controlled by the injection. The temperature in the bomb arising from the combustion is so high that the additional injected fuel ignites almost immediately after entering the combustion chamber. As soon as the fuel is cut off, no more flame is observed near the nozzle opening. Even the interrupted fuel flow caused by oscillations in the long fuel pipe may be made out on the first photograph of figure 25.

In this experiment as well as in others a slow rising of the center of the schlieren toward the spray direction - that is, upward, is observable. This motion takes place at a speed of about 1 m (3.28 ft.) per second. This change in direction may be explained by the fact that the main part of the combustion occurs in the lower part of the bomb space, causing the burned gases to flow upward to equalize the pressure. When the combustion took place in the upper part of the bomb, as in figures 17 and 22, the motion of the streaks was in the opposite direction. The very dark center of the schlieren appears always at the place where a particularly large quantity of fuel is burned. Uniform schlieren may therefore be taken as an indication of good atomization and vice versa.

The experiments with the Bosch spray nozzle show a strong dependence of ignition time lag on the temperature. In the absence of turbulence, the air density,

$$\gamma_L = \frac{P_L}{29.3 T_L} \text{ [kg/m}^3\text{]}$$

and the oxygen concentration

$$c_o = \frac{0.21 P_L}{848 T_L} \text{ [mol/m}^3\text{]}$$

*Wentzel (reference 30), assuming certain coefficients of heat conduction, computes the time of evaporation of a fuel drop of 0.01 mm (0.039 in.) diameter at 550° air temperature to be about 0.0005 second, much shorter than the usual ignition lags in the engine. His assumed coefficient of conductivity appears, however, to have been too high.

proportional to it, were of considerable importance. A large oxygen concentration apparently favors rapid chemical reaction quite appreciably. The observation of Neumann (reference 20), arrived at from theoretical considerations, that "the higher the oxygen concentration the lower the air temperature may be without increasing the ignition lag," appears in our tests to have been fully verified.

The variation of ignition time lag with air density and temperature is shown in figure 42. The curves are separated by 30° temperature differences. Since no accurately determined temperature for each curve was possible, the actual temperatures are given at each point. The points still further removed from the curves may be ascribed to errors in measurements and the choice of the variable fuel charges. It may be seen from these curves that decreasing the temperature is more effective in increasing the ignition lag than decreasing the air density. Again, it should be noted that these values hold good only for undisturbed air and even temperature distribution in the bomb.

2. Combustion pressures and temperatures.— The pressure curve was obtained with the quartz indicator shown in figure 5. It was first tested and calibrated for static pressures. The oscillograph loop was likewise calibrated so that measurements on the pressure could be obtained. The pressures indicated by the quartz indicator were found to be independent of the temperatures. The tubular voltmeter was connected in the same manner as in earlier experiments in the Dresden laboratory. The motion of the valve pintle recorded on the oscillogram was obtained by means of another loop, utilizing the change in magnetic field of a magnetic loud speaker, whose armature was connected to the valve pintle. The differential curve of motion, not the pintle lift itself, was thus obtained, which was all that was required.

Two oscillograms are shown in figures 43 and 44. The corresponding photographs are given in figures 24 and 25. Since a quartz indicator measures only differences in pressure, the compression pressure just before injection, was taken as reference pressure. This pressure was determined for each test by direct measurement. The indicator was connected through a relay when the bomb had attained a suitable pressure and had been disconnected from the compressor. The slight decrease in temperature and pressure between time of start of ignition and start of recording is to be attributed to heat losses occurring in between. On all os-

cillograms, strong jags or dents may be observed. These have nothing to do with the pressure in the bomb, but obviously arise from mechanical and acoustic disturbances. As they are strongly magnified they are particularly noticeable, though they do not affect the validity of the pressure curve. The period between the lift of the pintle valve and the start of deflection on the pressure curve, is the ignition lag t_{vp} as determined by the quartz indicator.

The period from the beginning of the pressure rise to the point of maximum pressure is the combustion period t_p .

The temperature rise is similarly shown on the oscillograms. A highly sensitive thermocouple using thermoelements of one of the noble metals was employed, making high magnification unnecessary. By adjusting the zero line of temperature before ignition, and then connecting the thermocouple, the temperatures during the combustion were indicated. The thermocouple was calibrated by comparison with another thermocouple and millivoltmeter in a series of bomb tests in which the slow cooling of the air was observed. Noble metal elements of 0.1 mm diameter were employed for the thermocouple which was placed about 20 cm (7.87 in.) from the nozzle opening. The elements were not sufficiently sensitive to record rapidly varying temperatures, so that the maximum temperature t_{max_0} of about $1,250^\circ$ indicated on the oscillogram is not the actual maximum temperature of the flame.* Similarly, the ignition time lag t_{vtemp} indicated by the sudden rise in temperature is not a true indication of the actual time lag. It may be seen, at any rate, that the steep rise in temperature during combustion is followed by a similarly strong temperature drop after the heat exchange has been effected. The temperature t_2 that was calculated from the amount of charge without taking heat losses into account (fig. 36), was reached about 1 second after ignition when the temperature had begun to fall. Due to heat conduction at the large bomb surfaces the temperature, and with it the pressure, falls off to the original value rapidly only 2 or 3 seconds after ignition, according to the amount of fuel injected. Figure 45 shows the ignition time lag t_v , time required

*E. Schmidt (reference 25) made similar tests on a precombustion chamber diesel engine, using the same diameter wire for his thermoelements, and declared the maximum temperatures thus obtained to be false.

for combustion t_p , and pressure increase Δp , as obtained by the different methods - that is, by the flame photography, temperature, and pressure, as function of fuel charge. For one and the same experiment, large differences were obtained for the ignition lag by the different methods. The smallest and most accurate value is given by the flame photograph. The pressure rise lags a little behind while the thermocouple lags very much behind and gives a false value for the ignition lag. This is especially true when small fuel charges are used, in which case it takes some time for the flame to reach the thermocouple and it therefore receives heat by radiation instead of by direct contact.

For measuring the times of complete combustion the reverse is true. The observable flame appears for a shorter time on the photograph than the corresponding pressure rise on the oscillograms. The pressure method is doubtlessly the more accurate, since it is probable that near the end of combustion the flame is no longer bright enough to affect the film. The spectroscopy method would prove very useful in this connection for yielding more accurate information on the combustion.

The pressure depends in a definite way on the amount of fuel injected. The computed linear pressure rise is not attained, however. As shown in figure 45, the maximum pressure for small fuel charges is well under the computed value, due to large heat losses at the wall. For higher charges a higher maximum pressure than that corresponding to the computed value using the polytropic index $n = 1.35$ was obtained, the difference amounting to about 0.8 atmosphere.

3. Ignition lag for single-orifice nozzle. - The effect of the atomization and dispersion on the combustion were more closely investigated, using a Bosch single-orifice pintle valve of 0.5 mm (0.0197 in.) diameter, type DLOS V 244. From previous spark photographs it was found that for equal fuel quantities the single-orifice nozzle gave somewhat longer injection periods and coarser atomization than the other type nozzle. Two photographs obtained with this nozzle are given in figures 26 and 27. Figure 26 was obtained at relatively low temperature but high air density. The ignition starts rather slowly and with such feeble flame that only after the sixth picture is the formation of schlieren observable. It is a noteworthy fact that this nozzle has a strong tendency for after injections,

as shown by the afterburning in figure 27. The strongly drawn-out injection of figure 27 clearly indicates the possibility of regulating the combustion process by means of injection. Also, in these tests the ignition starts at the outer edge of the spray. The ignition lag for various initial temperatures and air densities is shown in figure 46 which is similar to figure 42 except that for the same temperature and air density the ignition lag is longer.

4. Injection against an impact plate.— The space available for combustion in an engine is seldom as large as that in the bomb so that the spray comes in contact with the walls before it can fully develop. If the wall is too hot, cracking of the fuel may take place. If the wall is cool, the ignition may be delayed. Besides, the impact may sometimes cause the mixture to become coarser and less uniform than it would otherwise be.

Only a preliminary attempt to simulate engine conditions was made by placing an impact plate of 5 cm (1.97 in.) width in the bomb at 10 cm (3.94 in.) distance from the nozzle opening, and obtaining photographs, with the other conditions kept the same as before. Figure 28 shows that the atomization was in nowise improved by the presence of the plate, nor was the ignition lag decreased. The combustion of the fuel at the impact plate goes on very slowly. Ignition starts above the region affected by the impact plate. Although the flame for this photograph was weak, being near the lower limit of ignition temperature, the crowding of the schlieren in the neighborhood of the plate evidently shows that the largest portion of the spray energy was destroyed by the impact so that combustion took place right near the impact plate.

Figure 47 shows that the ignition lags are larger when the impact plate is used, no doubt due to the resulting decreased fineness of the atomization. These tests confirm the well-known requirement for efficient combustion, that the atomized particles should as far as possible be prevented from coming in contact with any walls, particularly if these are at the same or at lower temperatures than the air.

5. Motion of the spray during combustion.— The spray tip leaves the nozzle at the high velocity corresponding to the injection pressure, but soon meeting the high resistance of the air, slows down considerably. Elsewhere we have considered the velocities of nonburning sprays

(reference 9), and the results may be applied to our case for the spray before ignition. These speeds were obtained from a series of photographs and are given in figure 48 as a function of the depth of penetration.

The spray tip is accelerated by the sudden local pressure rise occurring at the instant of ignition. The spray velocity then rises or remains approximately constant during the combustion, after which it falls off very rapidly to a value below that corresponding to a nonburning spray. During combustion the spray is thrown about here and there, depending on the local conditions. If the large number of possible ways in which the burning may go on is taken into consideration, the distribution of the test points on the diagram is surprisingly good, so that the conditions in the bomb chamber, where there is no turbulence, are quite well represented.

VI. SPRAY INJECTIONS USING GERMAN BROWN COAL-TAR OIL

The apparatus is particularly well suited to the investigation of the properties of the different fuels. An extensive research program has been planned for the purpose of investigating different fuel oils, especially those produced in Germany. Only partial results from the data already obtained will be given here.

A variety of German unrefined brown coal-tar oil containing creosote was first tested. This fuel could be used satisfactorily in high-speed precombustion chamber diesel engines, as long as proper means were taken to heat the precombustion chamber. The fuel has a lower heating value of 9,359 k cal/kg (16,845 B.t.u./lb.), a specific weight of 913 kg/m³ (57 lb./cu.ft.) at 15°, and a boiling range from 193° to 360°. The percentage sulphur is 1.03 percent. The color is deep black. Naked-eye observation of the flame showed that the light instead of being dazzling white as in the case of the gas oil, was of a dull yellowish-red color which finally assumed a bluish tinge. This light did not produce a good picture on the film, the flame on 15 photographs taken with this light being barely recognizable though observed visually. Further investigation is planned using more color-sensitive film.

The spray photographs (figs. 29 and 30) show the considerably larger ignition lags obtained with this fuel. Figure 29, obtained at 505°, shows the ignition first start-

ing in the fifth picture after injection has been completed. The flame seems to spread slowly to the other parts of the spray not explosively. Figure 29 is not so rich in contrast as the others so far obtained. This was due to the formation of a thick ashy deposit on the bomb window, after every 30 tests, or thereabout. Figure 30 shows the clearer photograph that was obtained when the deposit was removed. Raising the injection pressure to 500 atmospheres to improve atomization did not produce a shorter time lag.

Under the same conditions of temperature and pressure an ignition lag value three times as large as that obtained for the gas oil was obtained for the brown coal-tar oil. Figures 49 and 42 provide a clear comparison of the two.*

VII. SPRAY INJECTION OF A MIXTURE OF

COAL-TAR OIL AND GAS OIL

Further tests were made using coal-tar oil. Although the temperature in the bomb was raised to 560° , which was the highest temperature attainable, in no case could ignition be started by using pure coal-tar oil. The fuel had a lower heating value of 9,000 k cal/kg (16,200 B.t.u./lb.), a specific weight of 1,044 kg/m³ (65.2 lb./cu.ft.) at 15° and a boiling range of 210° to 360° . The color was deep black. The reason for the failure to ignite may be understood from the fact that the ignition temperature of the pure coal-tar oil as determined by Jentzsch, was above that of the gas oil so that ignition might have been expected at a temperature above 600° . The fuel appears to be, however, altogether unsuitable for spray injection as was learned from experiments on a Junkers diesel conducted at the Dresden machine laboratory.

A mixture of 50 percent coal-tar fuel and 50 percent gas oil was therefore used for these experiments. With this mixture reliable ignition occurred at 440° , but still with unusually long ignition lags. The gas oil did not, therefore, act as a kindling fuel having its own ignition lag, but only served to improve the igniting qualities of

*It should be noted that while the brown coal oil used in these experiments is unsuitable for engine fuel, other varieties of the same oil often give equal or shorter ignition time lags than gas oil.

the mixture in order for ignition to occur at all at the temperature used.

Figure 31 shows a photograph obtained for this mixture. Ignition does not start until after the end of the injection period, the combustion then continuing almost simultaneously along the whole spray length so that combustion is completed sooner than would be the case, for example, for an equal quantity gas oil with short ignition lag. This decrease in the combustion period with the consequently steep pressure rise account for the strong knock in an engine using fuels of low inflammability. If the ignition lag exceeds the injection period, regulation of the combustion by varying the injection is naturally impossible.

Figure 49 shows that the ignition lag curves for the mixture are about the same as those obtained for the unrefined brown tar-coal gas. Investigations on the different fuels are being continued.

VIII. TESTS CONDUCTED WITH PRECOMBUSTION CHAMBERS

Extensive tests on diesel engines using domestic fuels have shown that coal-tar oil (steinkohlenteeröl) could be used efficiently in engines provided with precombustion chambers by introducing small changes in construction. This is due to the fact that the air already heated by compression receives additional heat on coming in contact with heated chamber walls, so that even those fuels that ignite with difficulty are ignited without excessive time lag.

After the failure of ignition with the pure coal-tar oil injection, the idea occurred of utilizing the favorable action of precombustion chambers on fuels of this kind. These tests are still in the initial stages, but some account of them will be given here.

Two forms of precombustion chambers were developed, the inside dimensions corresponding to those used for the Daimler-Benz engines. (See figs. 50 and 51.) The prechamber of figure 50 shows the usual Daimler-Benz construction. It is directly screwed on to the cover of the cylinder bomb. The insertion of an adjustable heating coil in the precombustion chamber made possible the investiga-

tion of the starting of the combustion process. Figures 32 and 33 show photographs obtained with the precombustion chamber of figure 50. The outlines of the preheating chamber are observed in both pictures at the upper edges of the photographs. Figure 32 corresponds to the initial burning process in a relatively cool engine. The air in the bomb was at an initial temperature of 285° . By heating the coil for 30 seconds, however, strong ignition was obtained. The second photograph of figure 32 already shows a strong, deeply penetrating flame, which gets shorter and loses brightness in the succeeding photographs as the pressure in the chamber decreases. In spite of the moderate fuel quantity of 70 mm^3 (0.0047 cu.in.), the precombustion chamber allows the combustion to be spread over a longer time than would otherwise be the case. The pressure in the engine therefore rises less steeply, but the conversion of the heat energy occurs at lower efficiency.

Figure 33 simulates conditions in an engine with strongly cooled precombustion chamber; for example, after a long idle run. Since the heating coil is not used, ignition is long delayed and gives rise to small increase in pressure. The flame first appears in the fifth photograph, appearing dark because of the blue filter that was used in place of the green. The flame is still more drawn out along its length. It must be borne in mind in connection with bomb tests that the decrease in pressure in the main combustion space does not occur the same way as in the engine by the motion of a piston, which clears the precombustion chamber more quickly of the burned gases and therefore shortens the burning periods. The values for the combustion periods obtained in these tests with bombs having precombustion chambers should not be applied directly to the engine as they would always lead to errors. Using fuel quantities of 100 mm^3 (0.0061 cu.in.), somewhat larger than the prechamber was designed for, periods of combustion of as long as 2 to 3 seconds' duration were observed by eye. It is therefore clear that these values should be used with the greatest caution for comparison.

In order to simulate conditions in a warm engine, a second precombustion chamber (fig. 51) was planned. This chamber was strongly heated electrically, to assure a positive temperature drop between the heater and the air. Otherwise the construction followed that of Daimler-Benz. The inset a (fig. 51) was drilled with 30 holes 1.5 mm (0.059 in.) diameter each so as to secure a larger heating surface for the air streaming in and out of the prechamber.

The amount of heating could be regulated and the temperature measured by a thermocouple using noble-metal elements placed in the inset 5 mm (0.197 in.) below its upper surface.

Two photographs taken with this prechamber are shown in figures 34 and 35. They show the combustion period to be much shorter than was the case with the unpreheated chamber. For figure 34 the heating was regulated to give an average temperature in the prechamber about equal to the temperature at the end of compression in the bomb. The air density in the prechamber was therefore equal to that in the bomb. As a result of the high temperature the ignition was very intense so that the first photograph of figure 34 already shows the burning mixture coming out of the prechamber. The force of percussion of the charge hurled into the bomb is not inconsiderable, the flames escaping from the prechamber opening at a speed of about 25 m/s (82 ft./sec.) and maintaining this speed during the 0.007 second represented on the first four photographs. After the main combustion shown on the first five photographs, there may still be observed a 25 mm (0.98425 in.) long weak flame coming out of the prechamber. Because of its low light intensity the flame appears as a silhouette on the photographs, but naked-eye observation confirms this afterburning.

Heating the precombustion chamber to 505° and the bomb to 450° , that is, creating a 55° temperature difference and hence a difference in density in the bomb and chamber, brought about a much more intense ignition (fig. 35) with rapid combustion and hardly any afterburning. The prechamber was, to be sure, charged with $2/3$ the fuel load, in this experiment. The even flame distribution in the bomb indicated excellent mixing of the fuel in the prechamber. Complete elimination of afterburning would be achieved by providing directly for a pressure difference in prechamber and bomb allowing a rapid passage of the fuel from chamber to bomb.

The ignition lag could not be determined from the precombustion chamber experiments since the start of injection into the prechamber could not as yet be indicated on the film. The use of a heated prechamber of this kind, however, is suitable for the testing of heavily igniting fuels under conditions approximating those obtained in the engine.

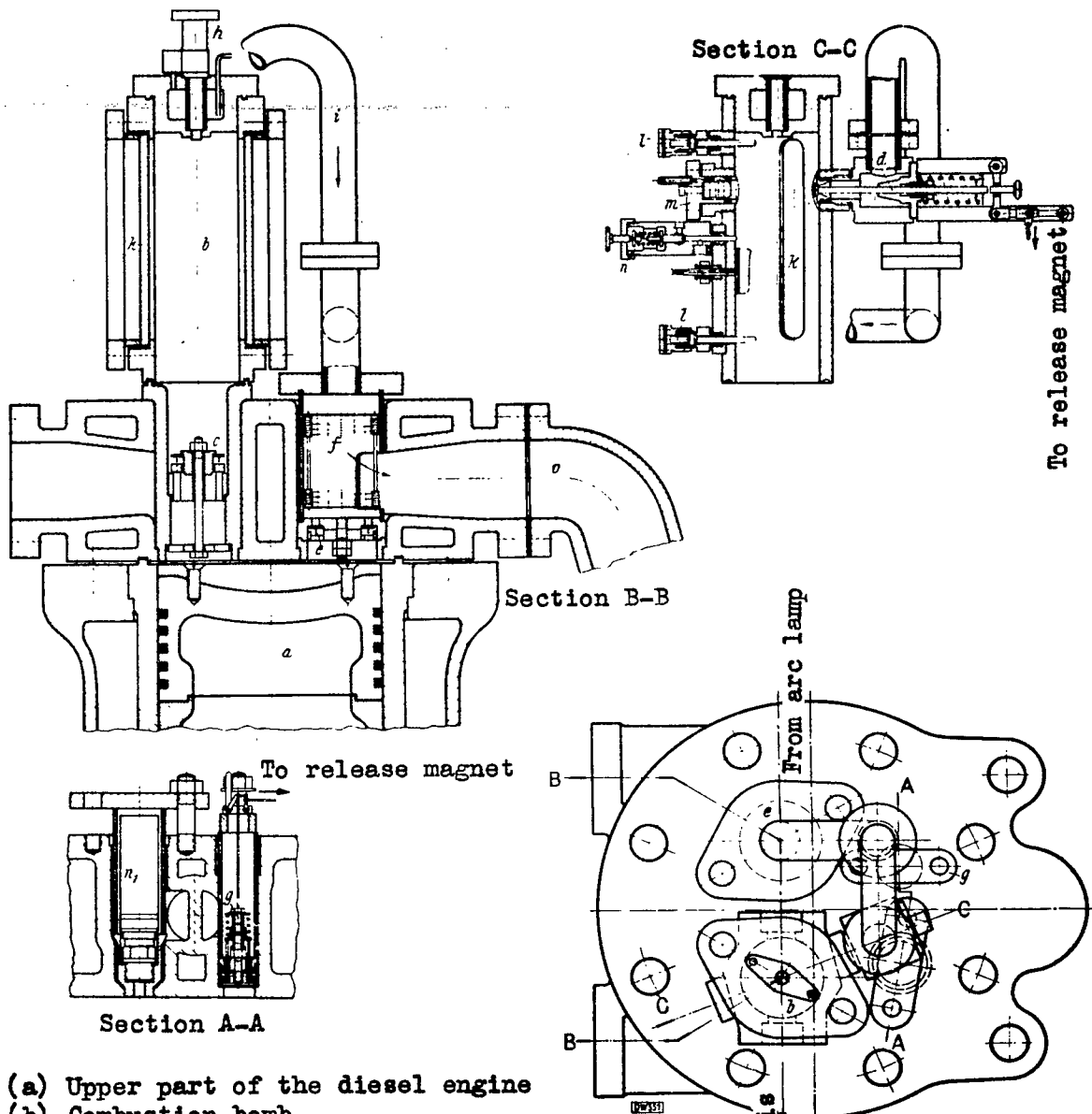
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National Advisory Committee
for Aeronautics.

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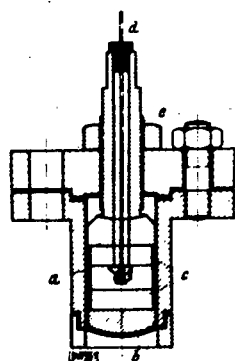
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- (a) Upper part of the diesel engine
- (b) Combustion bomb
- (c) Delivery valve.
- (d) Relief valve used during bomb preheating
- (e) Suction valve
- (f) Electrical preheating of air
- (g) Auxiliary valve for releasing the pressure
- (h) Fuel-injection valve
- (i) Pipe leading to receiver and cylinder
- (k) Observation windows of Sekurit-glass
- (l) Thermocouple
- (m) Quartz indicator
- (n, n₁) Safety valves
- (o) Intake manifold

Figures 1 to 4.- Drawings of combustion bomb.



- (a) Elastic sleeve
- (b) 1/10 mm copper membrane for sealing
- (c) Piezo-quartz crystal
- (d) Electrodes to amplifier
- (e) Fine adjusting screw

Figure 5.- Quartz indicator for combustion bomb.

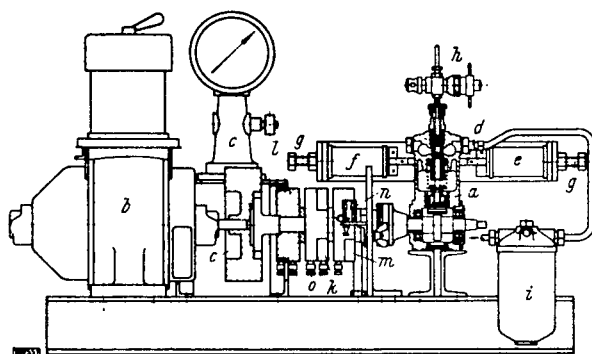
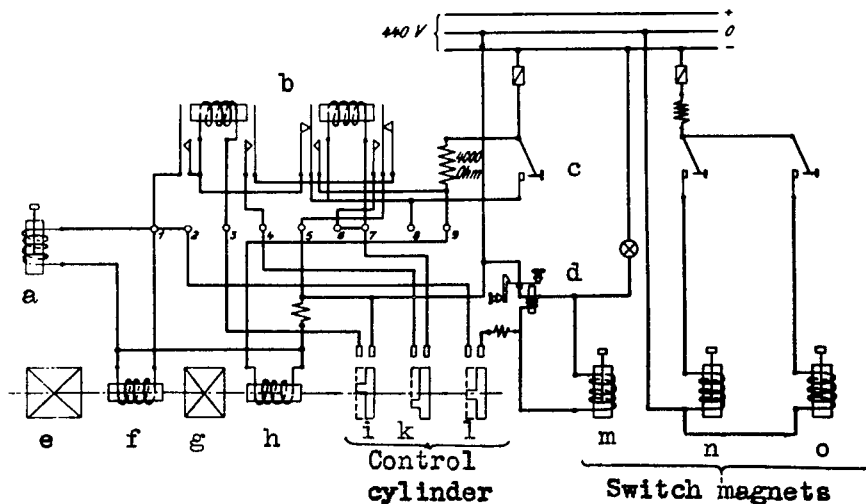


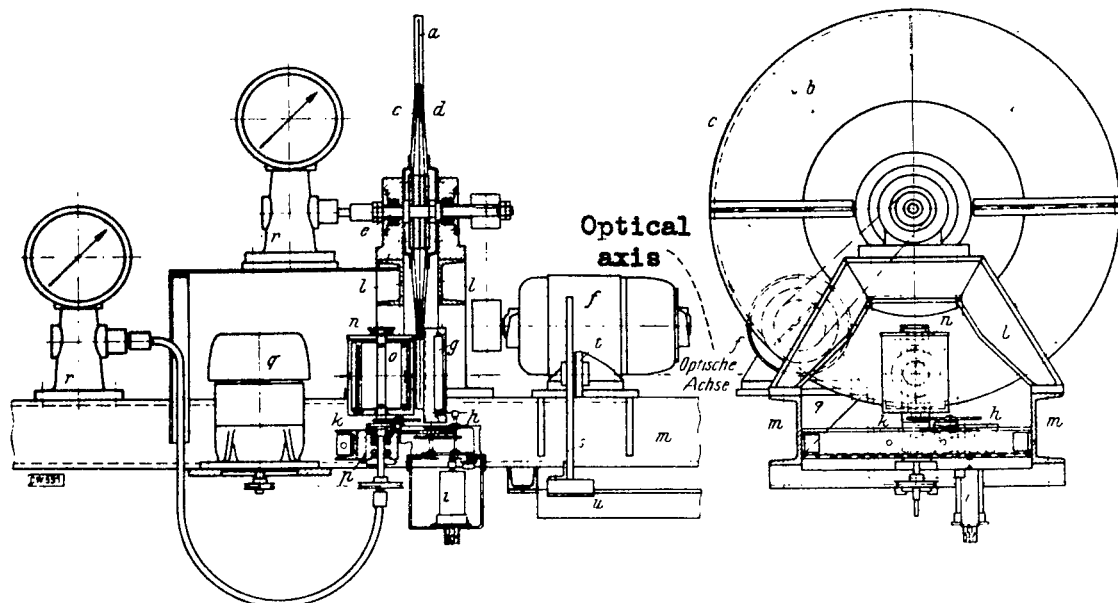
Figure 6.- Fuel pump with magnetic control.

- (a) Bosch fuel pump
- (b) Motor with control starter
- (c) Flywheel with tachometer
- (d) Injection-control rod
- (e) Magnet for filling
- (f) Magnet for cut-off
- (g) Stroke stops
- (h) Maximum pressure meter
- (i) Fuel strainer
- (k) Interruptor for injection
- (l) Interruptor for cut-off
- (m) Interruptor for release of photographic apparatus
- (n) Sliding contact adjustable for release of photographic apparatus
- (o) Sliding contact for control relay



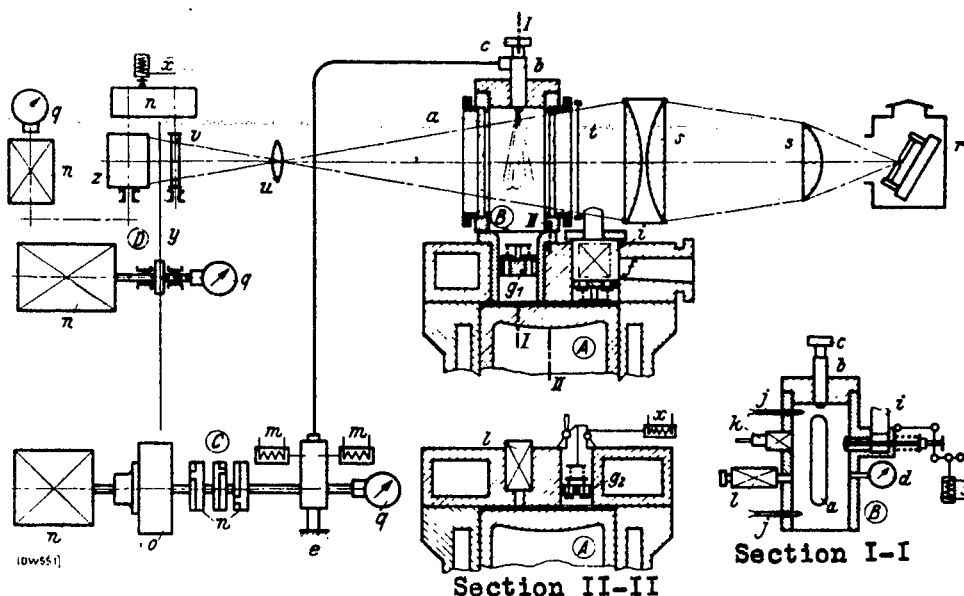
- | | |
|-----------------------------------|----------------------------------|
| (a) Switch magnet to oscillograph | (h) Switch magnet, out |
| (b) Control relay | (i) Pump, in |
| (c) Main release key | (k) Pump, out |
| (d) Control relay | (l) Camera |
| (e) Electric motor | (m) Instantaneous shutter camera |
| (f) Switch magnet, in | (n) Bomb by pass valve |
| (g) Fuel pump | (o) Compressor air valve |

Figure 7.- Hook up for control rings and switch magnet.



- | | |
|---|-----------------------------------|
| (a) Stroboscopic disk
(Novotex 0.8 mm) | (l) Support of disk |
| (b) 8 slits in disk | (m) Main support for apparatus |
| (c) Housing for disk | (n) Axle box |
| (d) Protective plate | (o) Film drum |
| (e) Shaft and bearing | (p) Bearing and drive of axle box |
| (f) Driving motor for disk | (q) Driving motor of film drum. |
| (g) Rotating diaphragm | (r) Tachometer |
| (h) Light cut-off | (s) Objective-lens holder |
| (i) Release magnet | (t) Objective |
| (k) Driving gear for light cut-off | (u) Optical bench |

Figures 8 and 9.- Photographic apparatus. Picture frequency, 550 per second. Shortest exposure time, at 1 mm width of slit, $T_1 = 0.75 \times 10^{-5}$ seconds. Stroboscopic disk, 680 mm diameter $N \leq 4,500$ r.p.m., 1.5 hp. driving motor. Film drum $N \leq 1,115$ r.p.m., 100 mm diameter, width 120 mm. Pictures $\frac{1}{4}$ natural size.



- | | |
|--|----------------------------------|
| (a) Observation window | (m) Control magnet for fuel pump |
| (b) Injection valve | (n) Coupling |
| (c) Appliance for measuring lift of valve needle | (o) Flywheel |
| (d) Manometer | (p) Driving motor |
| (e) Fuel pump | (q) Tachometer |
| (f) Suction valve in compressor | (r) Arc light |
| (g ₁) Delivery valve in compressor | (s) Condensers |
| (g ₂) Air valve | (t) Green filter |
| (h) Overflow valve in compressor | (u) Objective |
| (i) Overflow pipe | (v) Rotating diaphragm |
| (j) Thermocouple | (w) Light cut-off |
| (k) Quartz indicator | (x) Release magnet |
| (l) Safety valve | (y) Stroboscopic disk |
| | (z) Film drum box |

Figure 10.- Set up of entire apparatus.

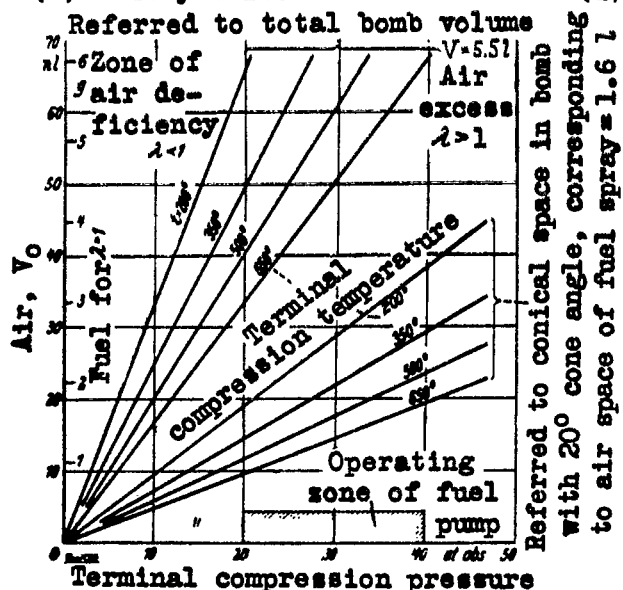


Figure 11.- Volume of air V_0 and fuel charge B ($\lambda = 1$) as a function of pressure and temperature.

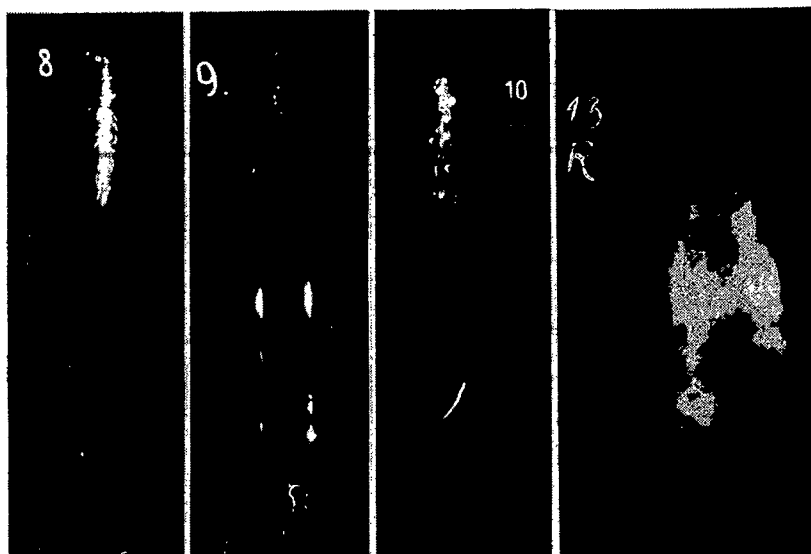


Fig. 12

Fig. 13

Fig. 14

Fig. 15

Figs. 12 to 15.-
Flame photographs obtained with the light of the fuel spray itself with ordinary camera, with shutter kept open. In the case of fig. 15 the camera is nearer to the bomb. Air density 12 to 14 kg/m^3 , temperature 400 to 450°, amount of fuel 230 mg. gas oil.



Figure 16.- Arrangement of photographic apparatus and bomb on the diesel engine.

Figure 17.- Test No. 66
using gas
oil $V_B = 190 \text{ mm}^3$. Injection pressure 300 at. Green filter used. Compression $p_c = 38.5$ at. gage. Temperature at end of compression $t_c = 415^\circ$. Specific weight of air $\gamma_L = 19.0 \text{ kg}/\text{m}^3$ $v = 415$ pictures/sec. Ignition lag $t_v = 0.0072$ sec.



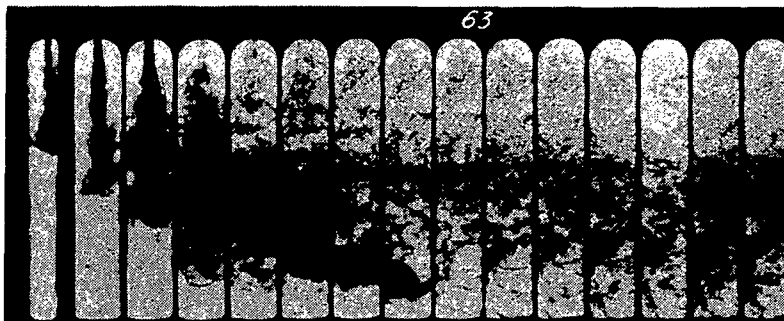


Figure 18.- Test No. 63
using gas
oil, $V_B = 190 \text{ mm}^3$, $P_E = 300 \text{ at.}$ Blue filter
used, $p_c = 35 \text{ at. gage}$,
 $t_c = 445^\circ$ $\gamma_L = 16.7 \text{ kg/m}^3$
 $v = 415 \text{ pictures/sec.}$
 $t_v = 0.0067 \text{ sec.}$

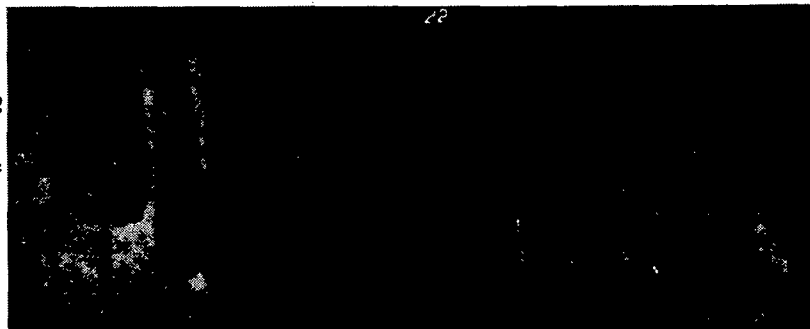


Figure 19.- Test No. 22
using gas
oil $V_B = 270 \text{ mm}^3$, $P_E = 300 \text{ at.}$ Green filter
used, $p_c = 40 \text{ at. gage.}$
 $t_c = 380^\circ$ $\gamma_L = 20.8$
 kg/m^3 $v = 445 \text{ pictures/sec.}$ Misfire.

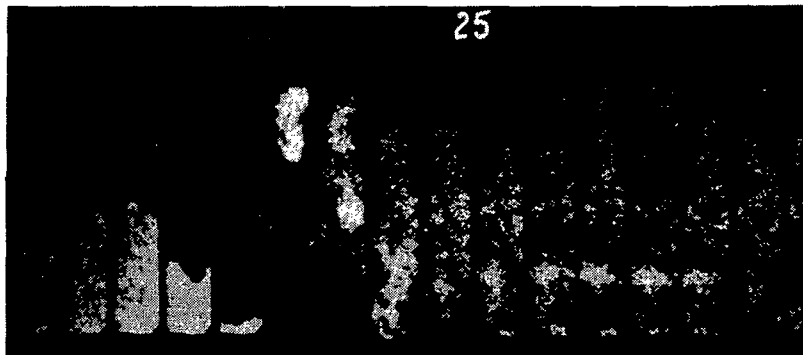


Figure 20.- Test No. 25
using gas
oil, $V_B = 250 \text{ mm}^3$ $p_c = 32 \text{ at. gage}$, $t_c = 405^\circ$,
 $\gamma_L = 16.1 \text{ kg/m}^3$ $v = 366$
 pictures/sec. $t_v = 0.0125 \text{ sec.}$ Flame spreads
slowly over spray which
was only slightly pre-
heated.

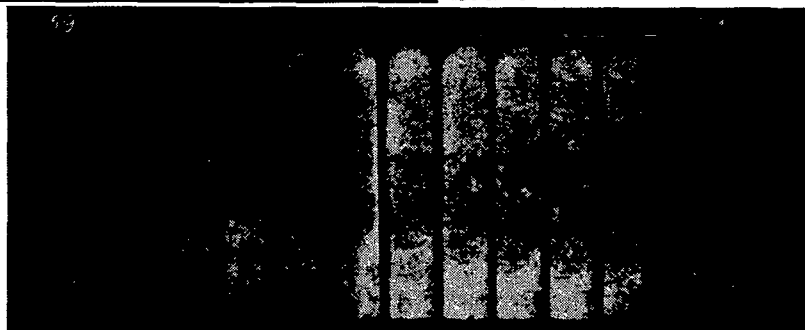


Figure 21.- Test No. 59
using gas
oil $V_B = 140 \text{ mm}^3$, $p_c = 23 \text{ at. gage}$, $t_c = 460^\circ$
 $\gamma_L = 10.7 \text{ kg/m}^3$, $v = 415$
 pictures/sec. $t_v = 0.0155 \text{ sec.}$ The schlieren from the seventh
picture on show the
start of combustion.

Figures 20 and 21.- Flame pictures at lower limit
of ignition temperature. Gas
oil $H_u = 10014 \text{ kcal/kg.}$ $\gamma = 887 \text{ kg/m}^3$, $P_E = 300 \text{ at.}$
Speed of fuel pump $n_p = 345 \text{ r.p.m.}$



Figure 22.- Test No.83 using gas oil, $V_B=190\text{mm}^3$, $p_C=24$ at. gage, $t_C=520^\circ$, $V_L = 10.2 \text{ kg/m}^3$, $v = 390$ pictures/sec. $t_v=0.0075$ sec. Injection with Bosch valve type DN12-SD12. Ignition proceeds rapidly up to core of spray.

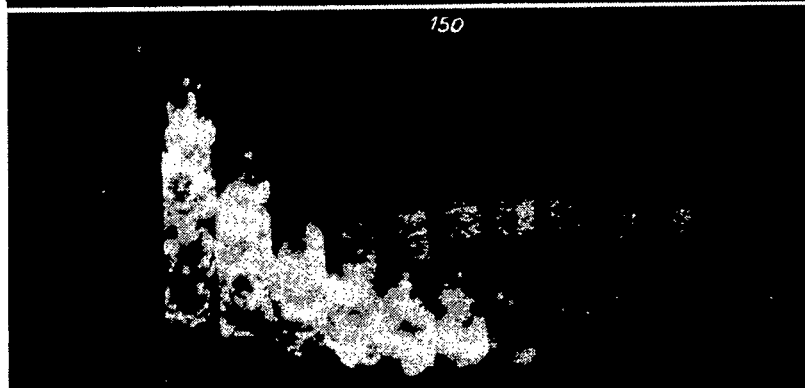
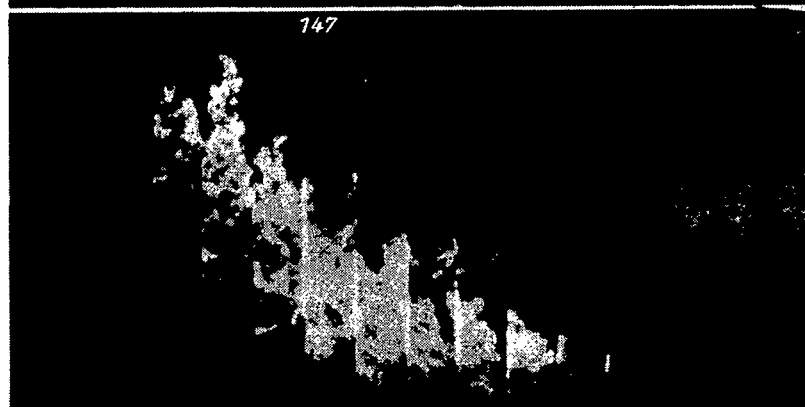


Figure 23.-Test No.150 using gas oil $V_B=190\text{mm}^3$, $p_C=29$ at. gage, $t_C=525^\circ$, $V_L = 12.5 \text{ kg/m}^3$, $v = 415$ pictures/sec. $t_v=.00314$ sec. Ignition at edge of spray. On account of the large quantity used the burning spray penetrates a distance greater than the artificially illuminated observation windows.



Figs.22 and 23. Flame pictures with small ignition lag. Gas oil used, $p_E = 300$ at. $n_p = 345$ r.p.m.

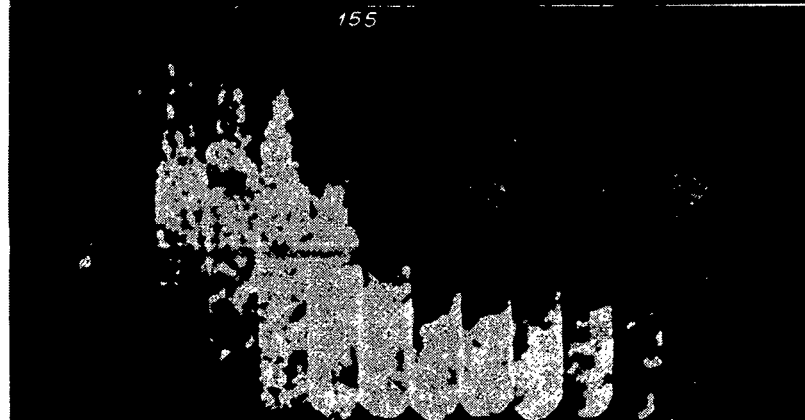


Figure 24.-Test No.147 using gas oil, $V_B=240\text{mm}^3$, $p_C=29$ at. gage, $t_C=560^\circ$, $V_L=10.25 \text{ kg/m}^3$, $v = 415$ pictures/sec. $t_v=0.0029$ sec. Time for complete combustion $t_B=0.0023$ sec. Maximum pressure from oscillogram $p_{\max}=35.4$ at. gage. Maximum temperature indicated by thermocouple $t_{\max_0}=1270^\circ$. See fig.19.

Figure 25.-Test No.155 using gas oil, $V_B=270\text{mm}^3$, $p_C=34$ at. gage, $t_C=545^\circ$, $V_L = 15.2 \text{ kg/m}^3$, $v = 415$ pictures/sec. $t_v=0.0024$ sec, $t_B=.021$ sec. $p_{\max}=40.9$ at. gage., $t_{\max_0}=1220^\circ$.

Figures 24 and 25.- Flame pictures at small ignition lag using gas oil. $p_E = 300$ at. $n_p= 345$ r.p.m.

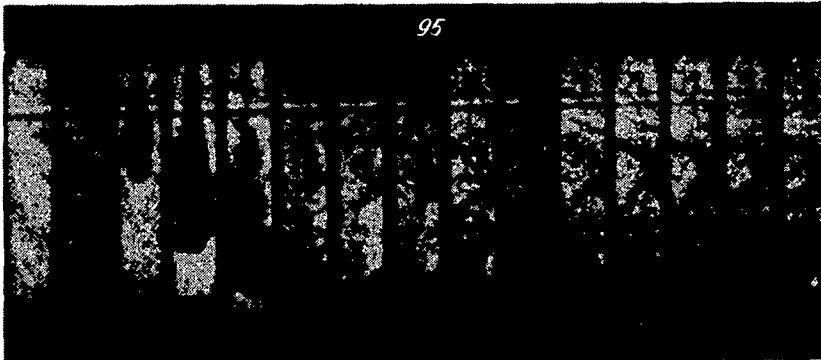


Figure 26.-Test No. 95, using gas oil, $V_B = 190 \text{ mm}^3$, $p_C = 40$ at. $t_C = 470^\circ$, $\gamma_L = 18.3 \text{ kg/m}^3$, $v = 390$ pictures/sec. $t_V = 0.014$ sec. Very large ignition lag. After injection clearly made out on fourth picture. Flame not very luminous.

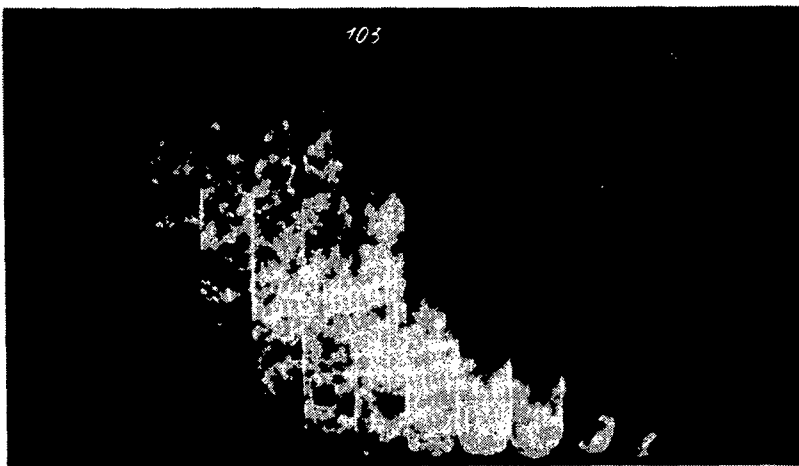


Figure 27.-Test No. 103, using gas oil, $V_B = 270 \text{ mm}^3$, $p_C = 40$ at. $t_C = 530^\circ$, $\gamma_L = 17.0 \text{ kg/m}^3$, $v = 390$ pictures/sec. $t_V = 0.0025$ sec. $t_B = 0.028$ sec. The injection is very much drawn out lengthwise, $t_E = 0.0165$ sec. (50 % longer than for No. 155 where the same fuel quantity with other type nozzle was used) In addition there is after burning.

Figs. 26 and 27.- Injection with Bosch single orifice needle valve. Orifice diam. 0.5 mm. type DLOS V244. Gas oil used, $p_E = 300$ at. $n_p = 345$ r.p.m.

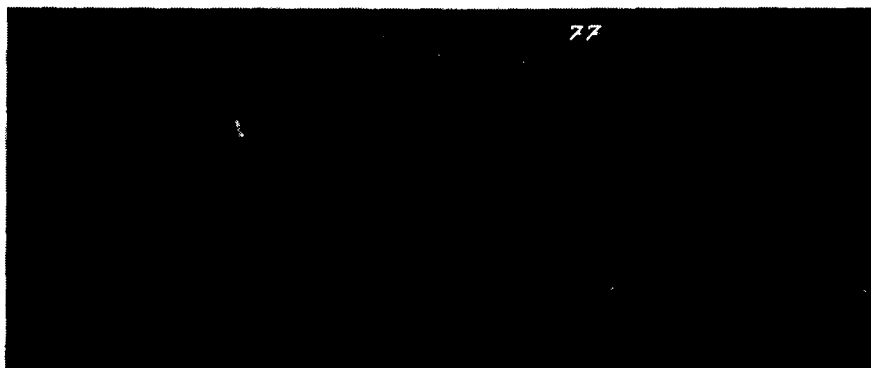


Fig. 28.- Injection against impact plate placed 10 cm. from nozzle opening. Gas oil used. $p_E = 330$ at. $n_p = 345$ r.p.m. Test no. 77. $V_B = 240 \text{ mm}^3$. $p_C = 47$ at., $t_C = 490^\circ$, $\gamma_L = 21.0 \text{ kg/m}^3$, $v = 415$ pictures/sec. $t_V = 0.011$ sec. The unheated impact plate neither improved the atomizer nor reduced the ignition lag. The combustion of the parts of the spray striking against the plate proceeds very slowly.

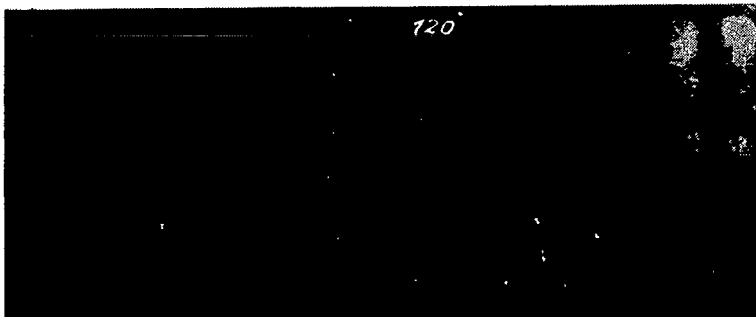


Fig.29-Test No.120, $V_B=150$ mm³, $p_c=30.5$ at., $t_F=505^\circ$. $\gamma_L=13.35$ kg/m³, $\nu=390$ pictures/sec., $t_v=.0115$ sec. Although the ignition lag is not too large, the combustion is slow. Flame only slightly luminous.



Fig.30.-Test No.126 using brown coal tar oil, $V=240$ mm³, $p_c=38$ at., $t_c=445^\circ$, $\gamma_L=18.1$ kg/m³, $\nu=370$ pictures/sec. $t_v = .0175$ sec. Ignition occurs long after injection.

Figs.29 and 30.-Injection with brown coal tar oil $H_u=9360$ kcal/kg., $\gamma=.913$, contains creosote, sulphur 1.03 %, $p_F = 300$ at., $n_p = 345$ r.p.m.

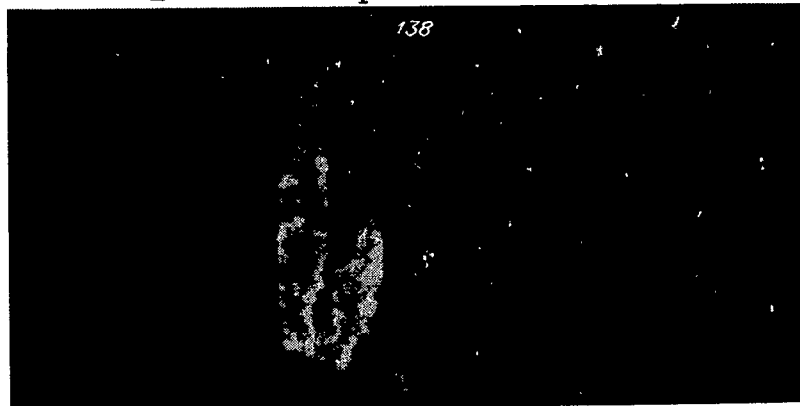


Fig.31.-Injection of a mixture of 50 % pure coal tar oil with 50 % gas oil. Coal tar oil $H_u=9000$ kcal/kg, $\gamma=1.04$ gas oil $H_u=10014$ kcal/kg, $\gamma=.887$. $p_F = 300$ at. $n_p=345$ r.p.m. Test No.138, $V_B=250$ mm³, $p_c = 34$ at., $t_c=510^\circ$, $\gamma_L = 14.75$ kg/m³, $\nu = 370$ pictures/sec., $t_v = .012$ sec. After the ignition lag, inflammation occurs almost simultaneously throughout the spray.

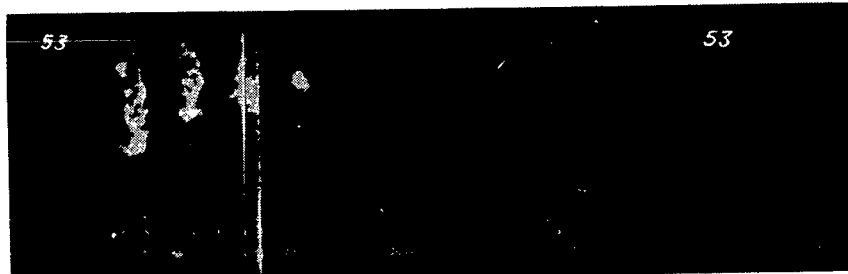


Fig.32.- Injection with prechamber of the Daimler-Benz type. Test no. 53 using gas oil. $V_B=70$ mm³, $p_c=30$ at., $t_c=285^\circ$ $\gamma_L=18.3$ kg/m³. Green filter used. 30 seconds preheating with heating coil carrying 33 amperes, $\nu = 250$ pictures/sec. The burning spray escapes with high velocity from the prechamber, but then slows down and the combustion is spread over a long interval.

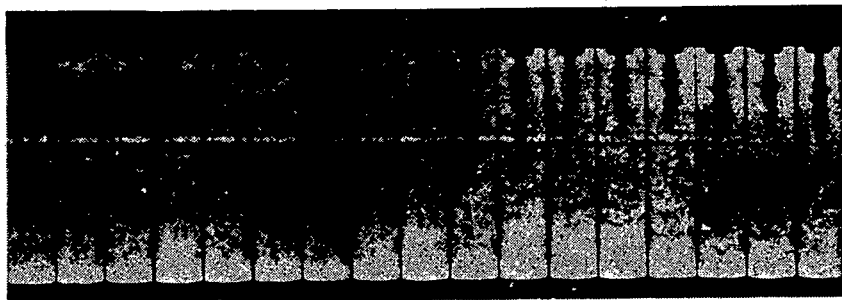


Fig.33.-Test No.57 using gas oil. Blue filter. $V_B = 70$
 mm^3 , $p_c = 30$ at., $t_c = 380^\circ$, $\gamma_L = 15.65 \text{ kg/m}^3$,
 $\nu = 250$ pictures/sec. Without heating to simulate
 strongly cooled prechamber. Small pressure in chamber.
 In spite of smaller fuel quantity, it took a longer
 time for combustion to be completed. Blue filter makes
 it difficult to distinguish flame from shadow.

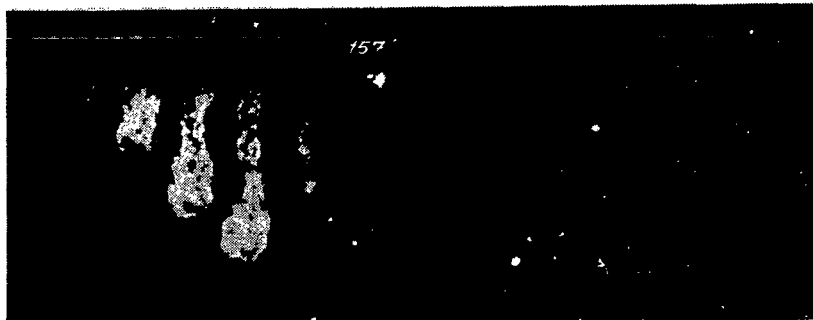


Fig.34.-Test No.157 using gas oil. $V_B = 70 \text{ mm}^3$, $p_c = 30$
 at. $t_c = 440^\circ$, $\gamma_L = 14.30 \text{ kg/m}^3$, prechamber:
 $t_K = 434^\circ$, $\gamma_L = 14.5 \text{ kg/m}^3$. Heating coil took 180 watts
 $\nu = 415$ pictures sec. Green filter used.

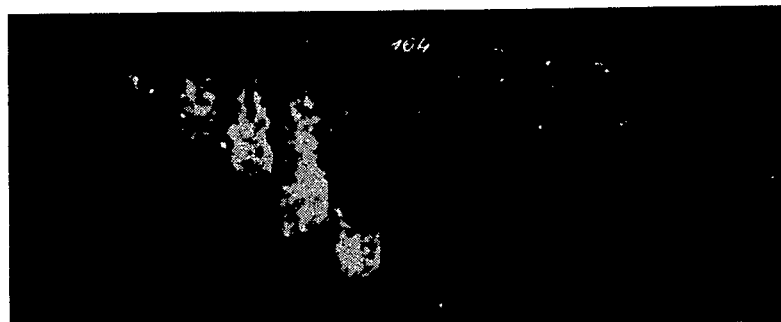


Fig.35.-Test No.164 using gas oil, green filter. $V_B =$
 45 mm^3 , $p_c = 22$ at. $t_c = 450^\circ$, $\gamma_L = 10.4 \text{ kg/m}^3$
 prechamber: $t_K = 505^\circ$, $\gamma_L = 9.65 \text{ kg/m}^3$. Heating coil
 took 250 watts. $\nu = 415$ pictures/sec.

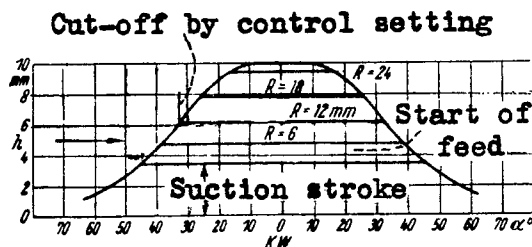
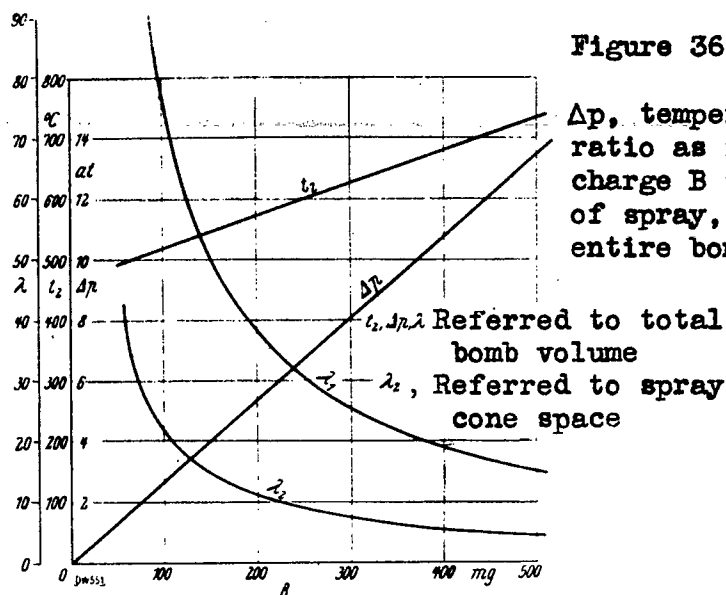
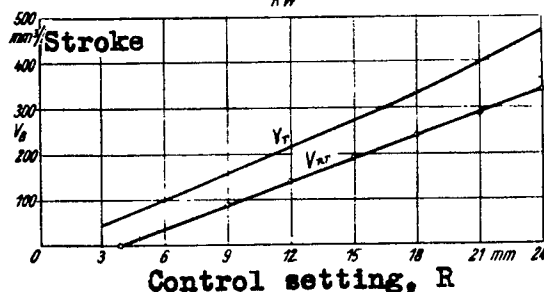
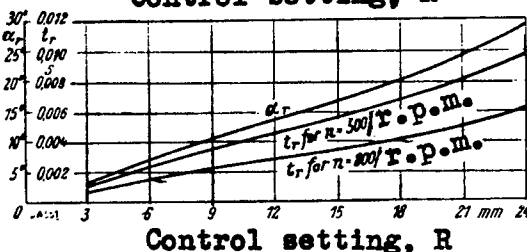
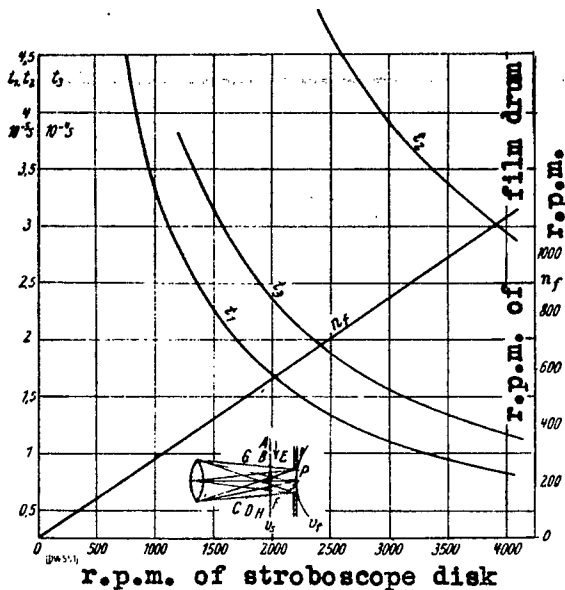


Figure 37.- Plunger lift versus cam angle.

Figure 38.- Volume of charge V_B for different regulator settings. V_r computed values, V_{pr} actual values obtained for $n=300$ to 800 r.p.m. and 300 at. injection pressure.Figure 39.- Computed value of spray angle α_2 and time of fuel injection t_r for different settings of governor.



$t_1 = \frac{AB}{v_s}$ Determines the amount of film blackening
 $t_2 = \frac{AB + CD}{v_s}$ Determines degree of definition
 $t_3 = \frac{EG + GH + HE}{v_s}$ Total exposure determining picture distortion
 v_s = Speed of slotted disk (m/sec)
 v_f = Speed of film drum (m/sec)

Figure 40.- Time of exposure as a function of stroboscope disk speed.

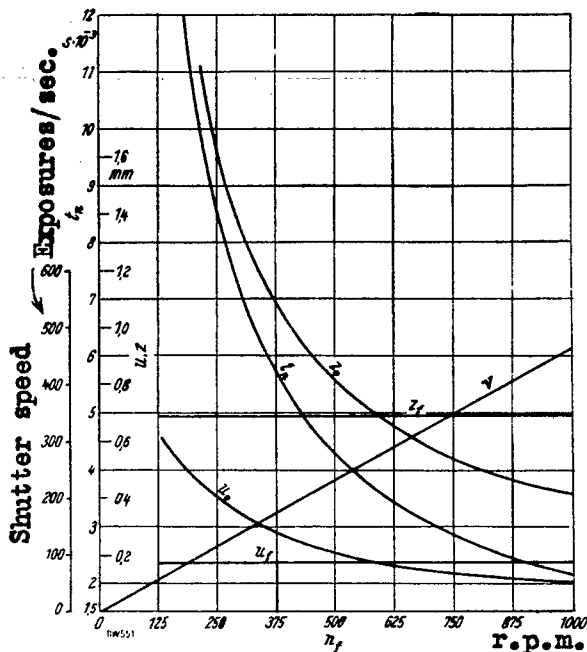


Figure 41.- Time per picture t_p , picture frequency v , degree of definition u , and distortion z as functions of the film drum speed n_f ; u_f , u_o , z_f , z_o produced by motion of film and object lens respectively.

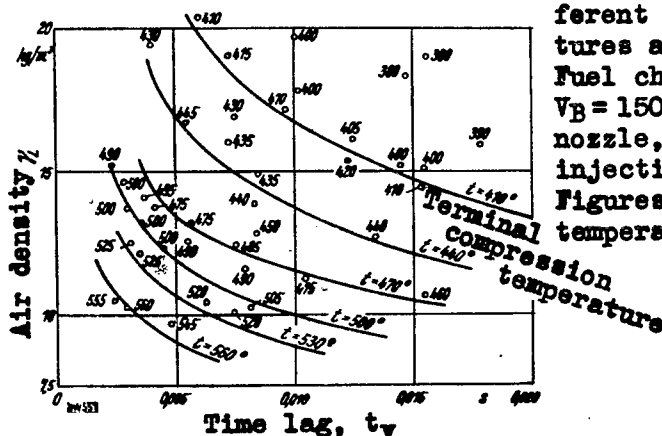


Figure 42.- Ignition lag times t_v for gas oil at different densities γ_L and temperatures at end of compression t . Fuel charge per stroke of pump $V_B = 150$ to 250 mm^3 , Bosch-Zapfen, nozzle, spray cone angle 4° , injection pressures 300 at. Figures at test points give air

temperatures in bomb before ignition.

Figure 45.- Ignition lag t_v , time for combustion to be completed t_b and pressure rise Δp . Comparison of results obtained from flame pictures and oscillogram. t_v flame, t_v pressure, t_v temperature, ignition lags determined from photographs, quartz indicator and thermocouple respectively. t_b flame, t_b pressure, time for complete combustion determined

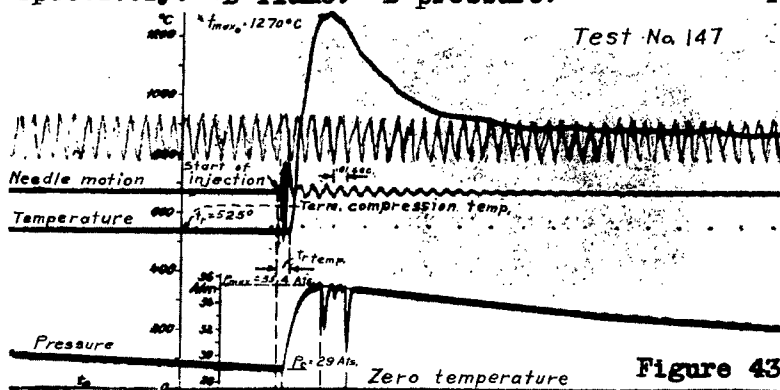


Figure 43

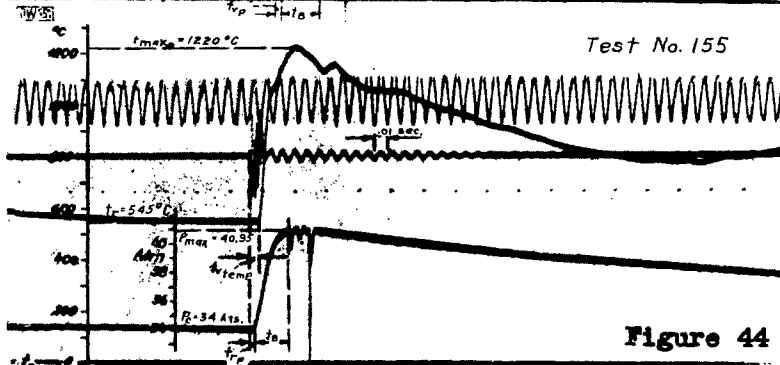


Figure 44

Figures 43 and 44.- Variation of pressures and temperatures during combustion.

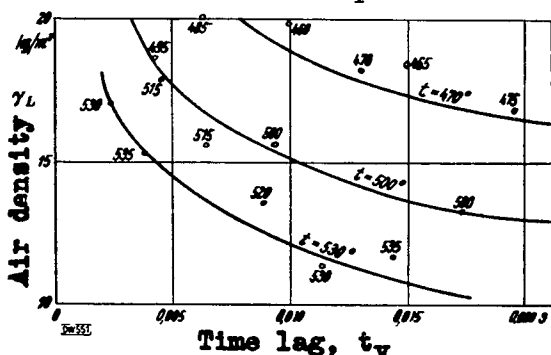


Figure 46.- Ignition lag t_v for gas oil at different air densities γ_L and temperatures at end of compression t . $V_B = 160$ to 250 mm³. Bosch single orifice needle valve 0.5 mm dia., injection pressure 300 at. Figures at test points give air temperatures in bomb before ignition.

from photographs and quartz indicator respectively. Δp , Δp_{th} , pressure rise as determined by quartz indicator and as computed from amount of fuel delivered respectively.

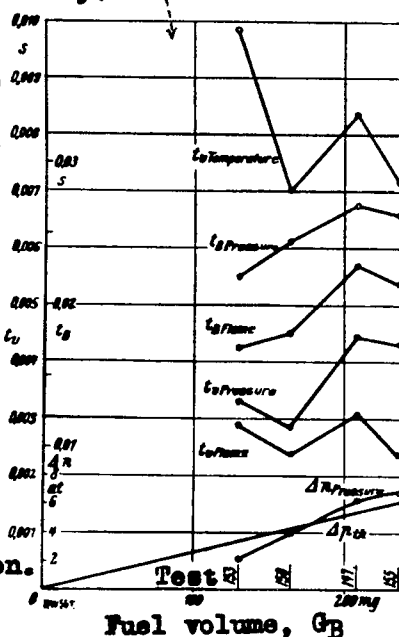


Figure 47.- Ignition lag times, for gas oil with injection against impact plate placed 10 cm from valve opening, for different temperatures t and air densities γ_L . Bosch-Zapfen nozzle 40° cone angle, injection pressure 300 at. $V_B = 160$ to 250 mm³.

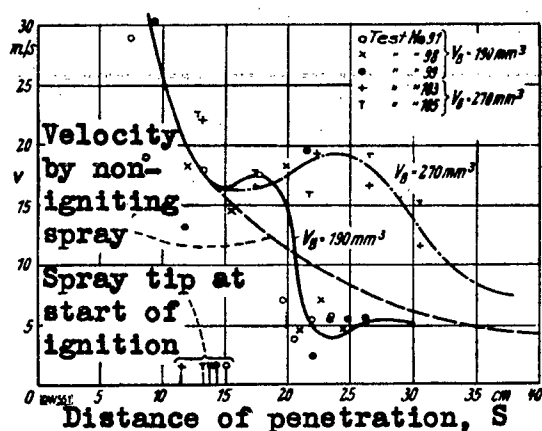


Figure 48.- Velocity of spray tip at different distances of penetration. Injection pressure 360 at. $\gamma_L = 19 \text{ kg/m}^3$. Bosch single orifice needle valve .5mm dia.

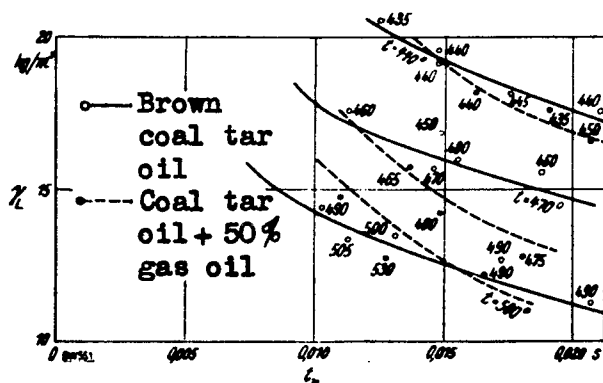


Figure 49.- Ignition lag times t_i , for brown coal tar oil, unrefined, and for coal tar oil + 50% gas oil. $V_B = 150$ to 250 mm^3 . Bosch-Zapfen nozzle 40° cone angle, injection pressure 300 at.

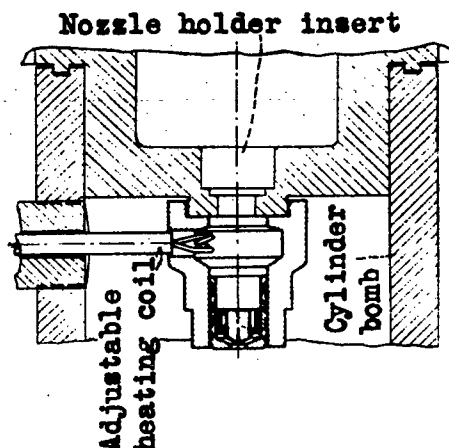


Figure 50.- Prechamber of the Daimler-Benz type.

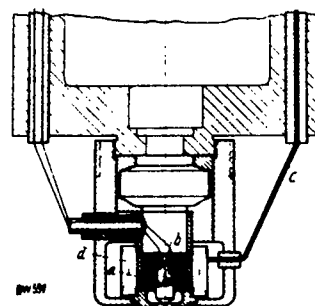


Figure 51.- Prechamber similar to Daimler-Benz type.

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